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GEWEX AMERICAS PREDICTION PROJECT (GAPP) SCIENCE PLAN AND IMPLEMENTATION STRATEGY

A SCIENCE PLAN FOR THE GEWEX AMERICA PREDICTION PROJECT (GAPP)

(7/20/00)

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1. INTRODUCTION:

Society's expectations for skillfull seasonal predictions have increased dramatically around the world and particularly in the United States as a result of the success in forecasting the 1997 ENSO and its impacts. Seasonal variations in climate are driven by feedbacks from the land to the atmosphere as well as the larger scale oceanographic forcing. The role of land in the hydrologic cycle is very complex and only now are we beginning to understand it. Recent advances in understanding have come through large field experiments that study the influence of land on the atmosphere at continental scales; through an improved capability of modeling land-atmosphere interactions, and, imminently, from a suite of new earth satellite systems designed to measure the properties of the earth's surface at high resolution.

The new national initiative described herein as the GEWEX Americas Prediction Project (GAPP) is aimed at addressing the role of land in seasonal prediction based on an integration of this new understanding, new measurement technologies and our new capability to model the coupled land-atmosphere system.

To a large extent GAPP is an extension of the highly successful GEWEX Continental-scale International Project (GCIP) that will be completing its observational phase in March 2001. This next phase is needed to realize GCIP's and now GAPP's ultimate mission, namely to develop a capability to predict variations in water resources on time scales up to seasonal and interannual as an integral part of a climate prediction system (NRC, 1998A). This mission remains a challenge that will only be addressed through the development of a new understanding of land surface processes and their interactions with the atmosphere; the exploitation of new technologies and the integration of this new knowledge on land-atmosphere interactions into a global prediction system.

A number of recent influential studies and reviews have highlighted the need to develop a prediction capability that effectively includes land surface processes. The National Research Council's (NRC) Pathways report noted, "the relatively simple problem of coupling land hydrology to the atmosphere remains elusive and yet is quite important" (NRC, 1999). An NRC hydrology report noted that "the development of scientific capability to detect and predict changes to the water cycle in response to natural and human-induced climate variability is a key priority research area" (NRC, 1999). A recent USGCRP Water Cycle study has indicated that a central question is "to what extent can variations in the global and regional water cycle be predicted?" (USGCRP, 2000).

The GAPP initiative outlined in this Science Plan extends the GCIP approach developed in the Mississippi River Basin to other climate regions of the USA and also advances the program focus from analysis to prediction thereby better positioning the hydrometeorological community to achieve the GAPP mission. In addition, GAPP has been designed to bridge the gap between the current understanding and capabilities of the climate community, and the requirements for a climate prediction capability that fully incorporates land surface processes and hydrology. Furthermore, GAPP will develop stronger links between the climate community and water resource managers that will utilize climate predictions.

This Science Plan outlines GAPP's strategy for building and delivering a land component for climate models and a capability to monitor and predict the components of water and energy budgets on all time and space scales. In addition, this ability to predict on climate time scales will be coupled to the needs of water resource managers to ensure that a future prediction system provides long-term national benefits from the management of this critical resource.

2. BACKGROUND:

2.1. The Emerging Water Crisis

The demand for water by the public in the USA is growing by an estimated 1.6% per year although the effects of this increase are currently being offset in some regions by decreased demands for irrigation water in agriculture. Increases in water demand are occurring in cities where urban growth is fueling the demand for domestic water; in localized areas of industrial growth where expansion requires more water for hydroelectric production and industrial cooling requirements; and, generally, in water management with increased requirements for ecological needs, recreation, and navigation on larger rivers. Neither the water supply nor the demand for water are evenly distributed across the country. Water supply varies with climate zone, ranging from relatively plentiful supplies in the East and Pacific Northwest to very scarce supplies in the semi-arid Southwest. As population increases and the ratio of demand to supply increases, new requirements for water are more difficult to satisfy and periods of drought are much harder to survive. This trend is particularly important in the southwestern US where annual water demands are rapidly approaching the average annual supply. In other areas, such as the Midwest, the economic implications of summer droughts are very large because irrigation demands for water cannot be met during these periods and the risk of crop failure becomes very high. Often during dry periods supply deficits are met by “mining” groundwater, a practice that has an alarmingly limited lifetime and severe environmental consequences. Furthermore, the policy framework needed to redistribute water through interbasin transfers has not been fully developed.

In the face of these growing regional demands for fresh water and growing supply uncertainties, such as a possible long-term trend towards decreased supply or increased year to year supply variability due to climate change, it is important that water managers have access to the best possible information on current and predicted states of water resource availability. As shown by Georgakakos et al. (1998), the use of accurate seasonal prediction information formulated in probability terms for one reservoir in

Iowa could lead to savings of more than $2 Million per year. These savings could be multiplied across the country with the production and appropriate use of accurate climate predictions at seasonal to annual time scales. However, for these benefits to be fully realized two obstacles need to be overcome. First, an ability must be developed to produce reliable hydrologic forecasts with lead times up to a year and with the range of uncertainties clearly specified. Second, water resource managers must be convinced of the benefits of relying on the forecast information based on its relevance and perceived accuracy. GAPP will focus on providing the scientific basis for accurate forecasts based on land-atmosphere, land process and hydrology studies on time scales up to seasonal and annual. It will also assist in building ownership within the water management community for these predictions so that conditions will be favorable when a comprehensive national or international climate prediction system is ready for implementation.

2.2. The GCIP Legacy

The Global Energy and Water Cycle Experiment (GEWEX) was initiated in 1988 to examine the global and regional energy and water budgets. In 1994 the pilot phase of the first and most critical of its five continental scale experiments known as the GEWEX Continental-scale International Project (GCIP) was launched in the Mississippi River Basin. The other four GEWEX continental scale experiments include the Baltic Sea Experiment (BALTEX), which considers land-atmosphere-ocean interactions for the Baltic Sea and its drainage basin; the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA), which considers the effects of tropical forests on the atmosphere; the GEWEX Asian Monsoon Experiment (GAME), which considers the role of land in determining spatial and temporal characteristics and intensity of the Asian monsoon; and the Mackenzie GEWEX Study (MAGS), which considers cold region processes and their influence on runoff into the Arctic Ocean.

These projects complement GCIP, and together they form a comprehensive assessment of land-atmosphere interactions on a global basis. Since its full implementation in 1995, GCIP has produced numerous results that have clarified the nature of land-atmosphere interactions. As outlined in the NRC GCIP Review (NRC, 1998A), Lawford (1999), and elsewhere, among other things GCIP has played a leading role in showing:

1. Regional water balances cannot be closed with sufficient accuracy using radiosondes to estimate moisture convergence and divergence. High frequency outputs from modern-era 4-D atmospheric data assimilation systems are needed to close regional water budgets with the degree of accuracy required for GEWEX.
2. During the summer, the presence and vigor of vegetation has a significant influence on evapotranspiration rates and the quantity and distribution of convective precipitation while soil moisture has an influence on the intensity and location of downstream precipitation.
3. The statistical properties and sub-grid variability of precipitation patterns can be characterized with non-linear algorithms resulting in significant improvements in hydrologic predictions.
4. The spatial scale and pattern of land surface heterogeneity can have significant effects on the nature of mesoscale convection and the magnitude of local moisture recycling.
5. The development of a land surface scheme can be substantially improved by developing better model representations of snow, vegetation, soil moisture, runoff and ground frost.
6. Land surface evapotranspiration and evaporation from the Gulf of Mexico are the primary moisture sources for summer precipitation in the Mississippi River Basin.

The full legacy from these insights and developments include improved land surface models (SSiB, BATS, Eta land surface scheme, etc.) now being used in climate studies and weather prediction by the academic and operational communities. In addition to incorporating these processes into models, GCIP has developed an infrastructure for the conduct of model intercomparison studies through the Project for the Intercomparison of Land Surfaces Parameterization Schemes (PILPS). Furthermore a new Land Data Assimilation System being developed by GCIP, NCEP and the Goddard Space Flight

Center (GSFC) holds promise of providing initial fields for climate models based on the assimilation of extensive surface data sets including soil moisture and variables derived from radiance measurements acquired from existing and next generation satellite data products as well as radar and in-situ precipitation measurements.

Among GCIP's major contributions have been improvements in NCEP's regional data assimilation capabilities and the ability to produce consistent gridded fields of aerological and hydrological variables over the continental U.S. on a systematic daily schedule. For the first time, these regional operational products are being archived and distributed as a basic resource for investigations of coupled atmospheric and hydrologic climate processes on spatial scales from local to continental and on time-scales from hourly to interannual. GCIP has also facilitated integration of data from a range of sources, including upper-air radiosondes, surface weather stations, rain gauges and stream gauges. It is also assembling a five-year (1996-2000) research quality data set of precipitation radar (based on NEXRAD WSR-88D), as well as supporting data from wind profilers and automatic weather stations. New observations of soil moisture have also been initiated under GCIP sponsorship and will become part of the nation's climatic information system.

Within GCIP, a number of strategies for the implementation of large-scale field experiments have been developed. GEWEX views GCIP as a flagship for its other continental scale experiments and, in many ways, these experiments have been modeled after GCIP. From a science management perspective, GCIP has drawn the meteorological and hydrological communities closer together in order to study land surface and hydrologic processes and their atmospheric interactions. Through the contributions of operational and developmental numerical weather prediction centers (NCEP and FSL) in its data assimilation activities, GCIP has made optimal use of the extensive data sets gathered routinely throughout North America and incorporated them into data sets for climate research. This initiative has also facilitated the transfer of new modeling techniques developed in academia to operations. In the future, GAPP will build on the strengths that GCIP has developed while expanding the community that participates in the project and building stronger links between the prediction and observational research communities.

The GCIP coupled modeling research was predicated on the hypothesis that the creation of regional-scale coupled models that simultaneously represent both relevant atmospheric and the land-surface processes, and the validation of these models against observations from GCIP, will improve our ability to:

(a) predict variations in weather and climate at time scales up to interannual; and
(b) interpret predictions of weather and climate in terms of water resources at all time scales.

GAPP will build its modeling efforts on the same hypothesis.

The implementation of model development in GCIP has followed two paths as described in the GCIP Implementation Plan (IGPO, 1993) and shown in Figure 2.1. On the “research” path are the longer term modeling and analysis activities needed to achieve the GCIP coupled modeling Research Objective, namely “to develop and evaluate coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins (NRC, 1998). GCIP focused on those research activities that created, calibrated, and applied coupled models of the atmospheric and hydrologic systems with priority given to research to improve climate prediction and to improve hydrological interpretation of meteorological predictions at time scales up to seasonal.

An “operational” path adopts new modeling methodolgies, and develops and implements the improvements needed in the operational analysis and prediction systems to produce the model assimilated and forecast output products for GCIP research, especially for energy and water budget studies. The regional mesoscale models also serve to test components of a regional climate model and can provide output for the evaluation of a coupled hydrologic/atmospheric model during the assimilation and early prediction time periods as a precursor to developing and testing a coupled hydrologic/atmospheric climate model. The output from three different regional mesoscale models is routinely compiled as part of the GCIP data set.

2.3. The Programmatic Context

Prediction on a seasonal basis can be achieved with empirical tools or dynamic models. Under some environmental conditions, empirical techniques have been useful in predicting precipitation anomalies, however, by their nature, these statistical approaches are only one step in developing the sound detailed understanding required for dynamic seasonal prediction. High-powered computers and new earth-observing satellite systems are creating opportunities to develop an understanding of the shorter time scale dynamics responsible for climate anomalies over land.

The US Global Change Research Program has recently recognized the importance of water and through an External Science Group has developed a Water Cycle Science Plan. This plan identifies three major global water cycle questions that the federal government is expected to address over the next decade./ These questions are as follows:

1. What are the underlying causes of variation in the water cycle on both global and regional scales, and to what extent is this variation induced by human activity? To address this question work is needed to quantify variability in the water cycle and to develop techniques for separating natural variability from that which is human-induced.
2. To what extent are variations in the global and regional water cycle predictable? This question can best be addressed by demonstrating the gorge of predictability of variations in the water cycle over a range of space and time scales and to establish a scientific basis for making predictions and estimates of uncertainty useful for water resource management, natural hazard mitigation, decision making and policy guidance.
3. How will variability and changes in the cycling of water through terrestrial and freshwater ecosystems be linked to variability and changes in the cycling of carbon, nitrogen and other nutrients at regional and global scales? To address this question observations and experiments will be needed to characterize the coupling and feedbacks of water, carbon and nitrogen cycles. In addition, a quantitative, predictive framework will be developed through the synthesis of concepts from different disciplines that utilize these data sets.

GAPP will be funded as one of several specific water cycle initiatives under the USGCRP. Accordingly, GAPP will ensure that its research contribute to the federal response to the research questions posed above. In particular GAPP will address issues related to prediction and monitoring, particularly as those questions can be addressed as research is directed towards achieving the GAPP missions.

World Freshwater Assessment Programme: Recently the World Water Council established a new program to undertake assessments on a routine basis. This initiative relies on good scientific inputs and techniques to effectively carry out its assessments. GAPP will contribute the scientific basis for the work done in the USA and through transferability studies to scientific efforts undertaken on a world wide basis in the assessment of water resources.

With the advent of new satellite systems such as EOS and ADEOS II, the World Climate Research Programme (WCRP) is implementing the second phase of its GEWEX program. Within the USA a strong national program involving NASA, NOAA

Figure 2.1. Research and operational paths for model development in GCIP.

and other agencies is needed to deliver the integrated program on the prediction of continental scale water and energy budgets that GEWEX envisions. Furthermore, to fulfill the expectations of WCRP, GEWEX will rely heavily on a follow-on to GCIP that emphasizes improved predictability based on an enhanced understanding of land surface processes at seasonal, and regional and global scales. GAPP is designed to meet this need.

However, GAPP must also be regional and local in order to develop strong ties with the water resource community at the watershed/river basin scale and to effectively cope with the hydrologic aspects of predictability questions. This result will be achieved by building on existing infrastructure (e.g., Office Hydrology) as well as innovating new ways of addressing prediction problems. GAPP will also give a high priority to the incorporation of land surface processes into global climate models. To fully achieve this objective, however, GAPP and the GEWEX Hydrometeorology Panel will need to work closely with the global components of the GEWEX and CLIVAR programs to plan and develop a comprehensive prediction system. In particular, GAPP will focus on incorporating high to medium resolution (10-50 km scales) land and land-atmospheric processes into Land Surface Models (LSMs) for both regional and global application.

CLIVAR, with support from dynamic models, is successfully contributing to the understanding of how tropical sea surface temperatures can be used in seasonal predictions during ENSO years. However, prediction studies also show that the evolution of climate over land areas for the annual cycle is dependent on initial moisture conditions and on the models' ability to predict the precipitation that, in turn, forces soil moisture and the land surface boundary conditions as the simulation unfolds.

GAPP will provide leadership in linking relevant GEWEX and CLIVAR activities by developing joint regional land surface modeling activities that are integrated with CLIVAR/ VAMOS/PACS oceanographic and experimental research. In December 1998, sixty countries met in Paris to commit themselves to undertaking CLIVAR. Based on agreements at that meeting, CLIVAR is looking to GEWEX to provide the necessary land surface modeling for improving global prediction systems. Accordingly, GAPP will work with appropriate projects and committees in GEWEX and CLIVAR to develop the process understanding and model parameterizations needed for global climate models and seasonal forecasting. These studies will focus on land-ocean-atmosphere interactions and the influence of large-scale circulation patterns on mesoscale processes. Together with CLIVAR/VAMOS/PACS, GAPP will provide the scientific basis for an end-to-end prediction system for America's water resources.

GAPP addresses recommendations contained in the recent NRC Review (1998A) and the Overview to the NRC Pathways Report (NRC, 1998B). As noted earlier it also builds on the valuable experience, models, data sets and expertise that have been developed through GCIP; actively contributes to the new initiatives of the GEWEX Hydrometeorology Panel (GHP) in developing global applications and coupled (land-atmosphere) models, and addresses the needs of resource agencies to have access to the latest information and technology. GAPP will report periodically on its success in pursuing its new strategy and will provide a final synthesis of its findings and experience in 2007 at its conclusion.

Precipitation patterns are also dependent on the feedback from land areas to the atmosphere that controls the climate, particularly during the summer when the atmosphere is more weakly forced by the ocean. During the 1990s, it has not been possible to observe patterns of global soil wetness to the extent required for seasonal prediction. However, through programs in NASA (satellite data) and DOE (high-speed computers) this situation is changing. With the anticipated computing power and data collection capability that these agencies are acquiring, GAPP should be able to realize significant gains in precipitation and soil moisture prediction skill by incorporating new land data and process understanding into much higher resolution climate models than are currently available.

In setting its strategic objective in 1995, the GHP anticipated the development and demonstration of a coupled global ocean-atmosphere-land model for climate prediction within the first five years after the millennium. It's strategic objective is stated as, " Working with other WCRP Initiatives by the year 2005 predict changes in water resources and soil moisture on time scales of seasonal to annual as an integral part of the climate system." The CLIVAR Implementation Plan identifies that the land surface process studies and resultant coupled land-hydrology component of a global climate model will be contributed by GEWEX. It is expected that the GHP efforts in coupled land area-hydrologic and atmospheric modeling will make a significant contribution to a coupled global ocean-atmosphere-land model for climate prediction

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2.4. The Climate Change Imperative

As the scientific community grows more confident in its assessment of climate change arising from greenhouse warming, and calls for action by the public and government become more pressing, the demands for unambiguous assessments of the effects of climate change on regional temperature, precipitation and runoff patterns will increase. In addition, the requirements for an adaptation strategy to deal with the effects of these regional changes are likely to increase. The reports of the Intergovernmental Panel on Climate Change (IPCC) are the basis for the current projection that the greenhouse warming will lead to an intensified hydrologic cycle, with an increase in the frequency of severe floods and droughts.

However, the 1995 report also recognizes that one of the main sources of uncertainty in these assessments is the inability to model complex land-atmosphere interactions in global climate models. Vegetation, soil moisture, snow cover and runoff all play important roles in the climate system that cannot be fully simulated by the current generation of climate models. GCIP has already made incremental improvements in regional land-surface models by incorporating more physical processes and through model intercomparison studies. Models developed for climate prediction studies must include all of the physics needed to simulate climate time scales; consequently GAPP models will meet the scientific standards for Global Climate Models (GCMs) used in climate change studies. GAPP will continue to improve the representation of land-surface processes and land-atmosphere feedbacks in these models, and in collaboration with GHP and CLIVAR, GAPP will work towards a well-tested, robust, universal land-surface model to support these critical climate change modeling applications.

3. GAPP OBJECTIVES:

In order to achieve its overall mission, GAPP will pursue two primary objectives, namely:

- To develop and demonstrate a capability to make reliable monthly to seasonal predictions of precipitation and land-surface hydrologic variables through improved understanding and representation of land surface and related hydrometeorological and boundary layer processes in climate prediction models, and
- Interpret and transfer the results of improved seasonal predictions for the optimal management of water resources.

These objectives will be achieved by undertaking a series of modeling and diagnostic studies, collaborative field projects, and observing activities. In particular, studies in support of the first objective will be structured to:

- Improve the understanding of land surface, precipitation, radiation and hydrologic processes over a continental domain at space and time resolutions appropriate for future climate and related hydrologic models,
- Identify, quantify and model the feedbacks between land surfaces (e.g. soil moisture and snow cover) and the atmosphere including monsoonal circulations and other large scale circulation patterns (e.g., The Pacific North American teleconnection pattern) that contribute to the predictability of continental precipitation, soil moisture, vegetation and runoff on climate time scales,
- Develop the process understanding, algorithms and parameterizations, data sets (including new satellite data sets), and data assimilation products necessary for transferring models from data rich to data sparse areas, and for the formulation of improved Land Surface Models (LSMs) for a broad range of applications including vegetation and biogeochemical cycling, and
- Develop a sophisticated high-resolution transportable land surface and boundary layer model with feedbacks that represent all the climate regions of the Americas, and the world.

The second objective will be achieved by projects carried out in close cooperation with water resource organizations and will rely heavily on the experimental prediction products generated by GAPP and other seasonal prediction experiments (e.g. by NOAA's Office of Hydrology, Climate Prediction Center (CPC), CLIVAR, International Research Institute (IRI)). This objective will be attained by:

- Developing an understanding and quantitative description of scale relationships between hydrometeorological variables for use in techniques to make outputs of climate models relevant to water resource managers through downscaling, calibration and probability distribution functions,
- In collaboration with international programs such as HELP, developing the scientific basis for hydrologic predictions and resource assessment systems that can be used for planning water and ecological resource strategies and projects,
- Undertaking demonstration projects to evaluate and operationally implement applications of seasonal predictions in water resource management, and
- Assessing the consequences of land use change and other environmental manipulations that cause potentially significant changes in regional climate and hydrology.

In order to achieve these objectives GAPP will rely on modeling and diagnostic studies and special coordinated field campaigns and data set development initiatives. GAPP will consist of the following seven components with time phased activities within each of these components. These components include: 1) Predictability of Land Processes, 2) Orographic Influenecs on the Regional Water Cycle, 3) Predictability of the North American Monsoon, 4) regional prediction, 5) assessing the transferability of predictability and prediction systems, 6) incorporating predictability into predictions systems, and 7) the role of predictions for water resources and related applications. The relationships between these seven components are shown in Figure 3.1.

Figure 3.1. Relationship between the various elements of the GAPP Initiative.

4. CONTRIBUTION OF LAND-ATMOSPHERE INTERACTIONS TO PREDICTABILITY:

4.1 Rationale

To fulfill the first objective of GAPP, it is necessary to identify, adequately understand, and capably model those land-surface features, phenomena, and processes that can contribute to improved monthly to seasonal predictions of precipitation and hydrologic variables. GAPP will address this goal in a study area that extends the Mississippi River basin previously studied under GCIP to include two new Large-scale Study Areas (LSAs) in the southwestern and northwestern U.S. (LSA-SW and LSA-PC, respectively). This extended study area provides an opportunity to investigate hydrometeorological interactions in more extreme environments that were inadequately sampled under GCIP and where water resources are particularly important. The surface water balance of the semi-arid Southwest, for instance, is markedly different from other regions of the U.S. where water is more plentiful. This aridity is reflected in the surface energy balance and the relative importance of ground-water processes. Snow and ice cover and topography are important influences on precipitation in mountainous regions throughout the west, and seasonal changes in soil-moisture status and vegetation are significant features of the land-surface/atmosphere interactions in the semi-arid southwestern U.S.

Land-memory processes will receive particular attention in GAPP, but it is recognized that the land surface and the atmosphere are a tightly coupled system that evolve together on both diurnal and seasonal time scales (Betts, 2000). Existing understanding from GCIP and other studies provides guidance on which aspects of the coupled land-atmosphere system are most likely to be associated with predictability. The storage of water near the surface as soil moisture and its storage on the surface as snow and ice cover are land-memory processes that can affect both the overlying atmosphere and runoff in streams or to ground water. Moreover, research suggests that the nature and seasonal progression of growing vegetation also represents a land memory, because the current nature and growth status of plants, which partly reflects past climate, controls current surface energy, moisture, and momentum exchanges. In addition, topography, although not a land memory as such, has a well-recognized influence on precipitation and hydrologic flows and, depending on the time of year, can determine whether precipitation falls in liquid or solid form.

Topography, snow cover, soil moisture, and vegetation all form an interactive system. For example, a large winter snowfall may produce more spring soil moisture as it melts, delaying the spring warming of the surface. This factor in turn will affect the timing and rate of initiation of growth of plants. Denser vegetation will provide more surface to intercept snow, but at the same time shade snow on the ground. Higher peaks receive more snowfall. Thus it is not possible to study each of these elements of land surface hydrology in isolation. Nevertheless, we express the scientific questions below specifically for each element to focus our research program. The planned research activities, however, will take into account the complexity and interactions of the system that we are studying.

4.2. Scientific Background and Questions

Topographic influences, land-memory processes (snow/ice cover, soil moisture, and vegetation status), and semi-arid hydrometeorology are discussed in greater detail in the following sections.

4.2.1 Topographic Influences

Subscale variability of topography has a marked influence on atmospheric convective processes and a strong control on surface hydrological flows. The interaction between atmospheric and hydrologic processes and topography necessarily involves questions of both temporal and spatial scale, as well as identification of significant, controlling topographic parameters, such as elevation, slope, and aspect. Such topographic parameters can be readily derived from digital elevation models at various spatial scales in the GAPP study area. On the other hand, precipitation data in mountainous areas are often poorly sampled by ground stations and poorly measured by radar. This factor places significant demands on analysis techniques and underlies the need for additional, strategically placed, ground stations.

Precipitating convective cloud systems in GAPP, and the North American Monsoon (NAM) system in particular, raise key issues involving interactions among the large-scale flow, topography, land-surface processes and convective cloud systems. These issues are of concern for both global and regional models. If adequately forced at lateral and lower boundaries, regional models with an adequate parameterization of the precipitation processes should be able to represent pure orographically generated precipitation reasonably well. However, key issues are associated with the initiation and life-cycle of convection over the North American Cordillera and the eastward propagation of organized convection that are not well understood and have not been properly represented by existing parameterizations.

Fundamental to GAPP and the North American Monsoon Experiment (NAME) are the indirect and remote effects of the North American Cordillera that are more complex than direct orographic forcing. Indirect effects include the orographic influences on the initiation of convection and heat-generated mesoscale circulations in mountainous terrain. Remote (far-field) effects involve traveling mesoscale systems not represented by existing (single-column) parameterizations. These research issues can be addressed using a hierarchical modeling approach based on (parameterized) regional-scale and (explicit) cloud-resolving models (Liu et al. 1999a, 1999b, 2000) that stem from oceanic convection studies (Grabowski et al. 1998; Wu et al. 1999). These models provide statistically meaningful results that contribute to the development of both GCMs and statistical models.

When hydrologic models capable of describing the horizontal movement of water are coupled to regional models, the resulting coupled models can represent the hydrologic response of catchments in response to topography. Testing the performance of such coupled hydrometeorological models is a priority for GAPP. However, statistical models of the influence of topography on precipitation, particularly at subgrid scales, are also required. Such models can be used to determine whether coupled hydrometeorological models do provide realistic simulations, and they can downscale precipitation patterns within the grid squares of coupled hydrometeorological models.

Statistical analysis of the interaction of precipitation with topographic parameters involves calibrating appropriate, single-point statistical models to the observed temporal variability (Hutchinson, 1991a, 1995a). Such models can conveniently separate long-term average precipitation patterns from anomaly patterns. These separate components can have different spatial scales and different topographic dependencies. This approach can be advantageous when using observations to calibrate topographic dependencies to support the spatial interpolation and statistical simulation of precipitation patterns. It can also help to identify key statistical parameters associated with longer-term change and predictability.

So far, most statistical analyses of the interaction between precipitation and topography have focused on the spatial interpolation of long-term monthly mean precipitation (Daly et al., 1994; Hutchinson, 1995b). This approach can be used to describe long-term average seasonal variability, which in turn is closely associated with patterns of natural vegetation. Moreover, interpolated monthly mean precipitation can also be considered to be one of the important parameters in a temporal-statistical model of precipitation. Monthly mean precipitation patterns are strongly modulated by topography. Elevation is usually the primary factor, but its influence varies spatially, thus invalidating the use of simple regression equations between precipitation and elevation (Chua and Bras, 1982; Hutchinson, 1995b). However, spatially coherent elevation dependency can be calibrated by using robust multivariate spatial analysis techniques such as thin plate smoothing splines (Wahba and Wendelberger, 1980; Hutchinson, 1991b, 1995b).

These techniques and others have indicated that the relative impact of elevation on precipitation patterns is two orders of magnitude greater than the impact of horizontal position (Hutchinson, 1995a, 1998; Running and Thornton, 1996). Thus, precipitation patterns usually reflect a topographic landscape that is exaggerated in the vertical, leading to a significant influence on precipitation patterns by relatively modest topographic features (Bindlish and Barros, 1996; Barros and Kuligowski, 1998). The spatial resolution of this dependence has been estimated as 4-10 km (Daly et al., 1994, Hutchinson, 1998). Slope and aspect also affect precipitation patterns at a similar spatial resolution (Hutchinson, 1998). Further study is needed to clarify the scales of the topographic dependency of precipitation. These scales may differ for different precipitation averaging periods and for windward and leeward precipitation generating processes (Barros and Kuligowski, 1998; Buzzi et al., 1998). More studies are needed to develop and calibrate robust spatial statistical models capable of representing the interrelationship between precipitation and the complex, extreme topography in the western U.S.

Statistical analysis shows that precipitation anomaly patterns arising from large-scale synoptic weather patterns display relatively broad spatial coherence and are relatively insensitive to topography (Hutchinson, 1995a). Such patterns are more readily represented in mesoscale meteorological models and are amenable to analysis in relation to broad scale circulation patterns (Walsh et al., 1982; Klein and Bloom, 1987; Lyons, 1990). It is fortunate that the statistical properties of such patterns can be more readily determined from less dense networks. Once determined, these anomaly patterns can be added to the background (long-term mean) topography-dependent patterns to generate more complex statistical models of precipitation patterns. Interpolating precipitation in this way can provide a data series that is appropriate as the input to monthly time-step hydrological models (Alley, 1984; Arnell, 1992; Pandzic and Trinic, 1992). Study is needed to identify the relative sensitivity of long term mean patterns and anomaly patterns to the factors that affect long-term change and predictability. This study will require close attention to the statistics of precipitation and due recognition of appropriate physical constraints where these can be identified.

Among the questions relating to predictability issues associated with topography that will be addressed under GAPP are the following:

1. Is it possible to define a robust statistical relationship between topography and precipitation across the entire GAPP study area? Specifically:

a. How sensitive are the parameters in such a statistical relationship to geographical location and interannual variability?
b. Are the parameters in such a statistical relationship different for liquid and frozen precipitation?

2. How does the influence of topography on precipitation, including its influence on whether precipitation falls in liquid or solid form, modify the magnitude and timing of hydrological flows in watersheds of differing spatial scale?

3. Can coupled land-atmosphere and regional climate models adequately reproduce the observed statistical relationships between precipitation and topography across the entire GAPP study area?

4.2.2 Snow, Ice and Frozen Soil

Snow processes are important in climate and weather prediction models because of the unique characteristics of snow, specifically its high albedo, low thermal conductivity, and the fact that snow and ice cover often exhibit considerable spatial and temporal variability. The control exerted by snow and ice on energy and water exchanges between the atmosphere and the underlying soil are therefore markedly different to other surfaces. In addition, the timing of snowmelt and the subsequent fate of melted water play an extremely important role in the hydrological response of catchments, especially in the western U.S.

Several studies have investigated the development and validation of snow submodels in climate models (e.g., Loth et al., 1993; Lynch-Steiglitz, 1994; Yang et al., 1997; Schlosser et al., 2000; Slater et al., 2000). These stand-alone model evaluations are encouraging but reveal that there are significant observational problems when validating snow/ice models. There are, for instance, challenges in accurately specifying the model forcing data. Measuring snowfall is difficult, especially in windy conditions. It is also difficult to specify a threshold temperature to characterize when precipitation falls as snow rather than rain, and although it is difficult to measure downward long-wave radiation, it is important to do so because this component is the dominant wintertime radiation flux (Yang et al., 1997). In the past, acquiring validation data has been problematic and scarce. There has been a general lack of measurements of snow temperature and density, and snow water equivalent and snow depth are often sampled infrequently, which makes model validation difficult, especially during the (often rapid) snow ablation period. Fortunately this problem is being mitigated to a significant extent by data collection under the MAGS and ARM-SHEBA projects.

Yang(2000;also see http://www.atmo.arizona.edu/~zly/snow.html) reviewed the snow/ice models used in weather forecasting, climate research, watershed modeling, and process studies. There are numerous snow/ice models, but the models that were used in the Schlosser et al. (2000) intercomparison study show substantial mutual disagreement because there is currently limited understanding of many important snow/ice processes. Poorly understood processes include the time-evolution of snow albedo, the representation of patchy snow/ice cover, sublimation, snowmelt and re-freezing, the retention and transport of melt water, and, not least, the mutual interaction between the snow/ice processes and the soil and vegetation processes within a comprehensive land-atmosphere model (Yang et al., 1997; Schlosser et al., 2000; Slater et al., 2000).

When coupled to climate models, snow/ice models do seem to be able to capture the broad features of the seasonal snow regime such as seasonal variations in the snow line. However, a convincing explanation of the still significant discrepancies in simulations of snow cover remains illusive because of the complex feedbacks between precipitation, air temperature, radiation, topography, vegetation, and snow. In the case of global models, for instance, the reasons for the frequent delays in modeled snowmelt at high latitudes in Eurasia and North America are not known (Yang et al., 1999), and similar unexplained weaknesses are also observed in regional climate model simulations for areas such as the Pacific Northwest U.S. (Leung and Ghan, 1999).

Thus, there are many difficult challenges remaining in the development of adequate representations of snow accumulation and snowmelt processes before predictive coupled hydrologic-atmospheric models can be expected to successfully reproduce the observed relationship between spring snow pack and subsequent summer rainfall in the southwest U.S. (Gutzler and Preston, 1997). By investigating the development of both uncoupled and coupled snow/ice models in regions with and without strong topography and studying the potential climate predictability associated with the snow/ice memory in North America context at catchment to regional length scales and at time scales up to seasonal, GAPP may meet this requirement.

Although there have been many studies of the effect of liquid soil moisture on climate, the effect of frozen soils on land surface processes and climate system have received little attention. However, about 70% of the earth's land surface experience seasonal freezing (Kinoshita, 1982) which often lasts several months and may reach a depth of 2-3 m, while 24% of northern hemisphere continents are underlain by permafrost (Zhang, et al., 1999a). Much of the GAPP study area experiences seasonal freezing which last several months, notably the upper Mississippi River basin and the Rocky Mountains (Zheng et al. 1999b). Because of the latent heat of fusion, freezing and thawing wet soil involves a very substantial uptake or release of energy so soils that freeze and thaw have, in effect, a large heat capacity. Freeze-thaw cycles influence the thermal and hydrological properties of the soil and this attribute has a significant impact on surface energy and moisture balances (Kinehita, 1982; Williams and Smith, 1989; Yershov, 1998) and, hence, on the climate system. Freezing soil increases its thermal conductivity and hence the soil heat flux, but it reduces its hydraulic conductivity and infiltration, thus increasing runoff, although near surface soil moisture may still increase due to restricted deep drainage. The existence of a thin frozen layer at the surface essentially decouples the moisture exchange between the land surface and the atmosphere.

There are substantial inter-seasonal fluctuations in the area of snow in the Northern Hemisphere and recent studies suggest there has been a decrease over the last 20 years (Armstrong and Brodzik, 1999) as air temperature has increased (by almost by almost 1 °C in the case of North America). On the one hand, if the area with snow cover is reduced, the areal extent and thickness of frozen soils might well increase. On the other hand, increased temperature may itself result in less frozen soil. Data sets on snow cover extent, depth, and snow water extent are becoming more available at the National Snow and Ice Data Center (http://www.nsidc.colorado.edu) to aid study of this phenomenon.

Among the predictability questions associated with snow and ice cover that will be addressed under GAPP are the following:

1. When operating within comprehensive land-atmosphere models in an uncoupled mode, can snow/ice submodels adequately represent the observed seasonal evolution of snow cover and snow water equivalent at catchment and regional scale and, when linked by horizontal routing models, can they correctly simulate the effect of snowmelt on the hydrological response of catchments?

2. When operating with observed snow cover and snow water equivalent imposed as a lower boundary condition, can regional climate models adequately reproduce observed relationships between snow/ice cover and regional climate?

3. Can coupled regional hydrometeorological models that include snow/ice submodels adequately reproduce the observed seasonal evolution of snow cover and snow water equivalent at catchment and regional scales and the associated hydrological response of catchments?

4. In regional models, what are the preferred model criteria that should be used to specify frozen precipitation?

5. How can the soil/freeze status of soil best be detected using remotely sensed data?

6. What is the response of seasonally frozen soils to changes in air temperature and snow cover extent?

4.2.3 Soil Moisture

The land, biosphere, atmosphere, and oceans are coupled together in an Earth system in which there is variability over a wide range of time and space scales. Variability and memory in this system are due to the cycling of water between reservoirs and may be strengthened by the development of feedbacks in the linkages between the reservoirs. Although the land fraction of the Earth is fairly small (30%), its distribution into large contiguous areas and its distinctive hydrothermal inertia cause significant variations in regional climatic systems.

Hydrologic states that have long memory, such as soil moisture, may serve to integrate past atmospheric forcing and enhance prediction skills for regional climates. Fennessey and Shukla (1999), Atlas et al. (1993), Bounoua and Krishnamurti (1993a,b), Xue and Shukla (1993), and Oglesby (1991) presented examples of numerical experiments, based on general circulation models, that indicate the sensitivity of climate simulation to initialization of surface soil moisture. Early studies by Delworth and Manabe [1993] showed that the presence of an interactive soil-moisture reservoir acts to increase the variance and add memory to near-surface atmospheric variables such as humidity, while Milly and Dunne (1994) identified and analyzed shifts in the atmospheric general circulation and hydrologic cycle in response to soil water storage capacity. Koster and Suarez (1996, 1999) introduced statistical measures to distinguish between inherent climate variability and variability due to the presence of land memory in the form of soil moisture.

The presence of feedback mechanisms can enhance land-memory phenomena. Thus, if positive feedback mechanisms are present in the coupled land-atmosphere system, an initial anomaly can persist through reinforcement at both climate and weather time scales. Cook and Ganadeskian (1991) and Cook (1994), for instance, showed that, following an initial soil-moisture anomaly, precipitation and the tropical general circulation are altered in ways that tend to reinforce the perturbed surface conditions. Brubaker et al. (1993) and Entekhabi et al. (1992) identified one such feedback mechanism that can reinforce surface anomalies. They found that when local precipitation is partially derived from local evaporation, reduced evaporation leads to reduced precipitation that, in turn, leads to further drying. Scott et al. (1997) and Vinnikov et al. (1996) demonstrated the importance of both soil-moisture reservoir size and the recycling of precipitation. However, there are conditions under which such simple feedback loops are not established. Thus, the relative roles of local versus external forcing for hydroclimatic anomalies over North America depends on factors that may either favor or counter drought or flood conditions (Giorgi et al., 1996).

On weather and storm event time scales, there is also evidence that initial soil conditions can reinforce the development of precipitating weather systems. At the regional scale, soil-moisture availability has substantial influence on elevated mixed layers and on associated “lids” on atmospheric instability that act to focus the release of convective instability and hence determine the distribution of the regional precipitation in time and space (Benjamin and Carlson, 1986; Clark and Arritt, 1995). Such coupling was clearly demonstrated by numerical modeling in GCIP (Paegle et al., 1996; Beljaars et al., 1996; Betts et al., 1996; Liu and Avissar, 1999a,b). These mechanisms are believed to have played a significant role in the Mississippi River floods in 1993. Castelli and Rodriguez-Iturbe (1993) showed that growth of baroclinic instability could be enhanced by anomalies in surface fluxes. Using numerical mesoscale atmospheric models, Chang and Wetzel (1991) and Fast and McCorcle (1991) showed that the evolution of summertime weather systems in the Midwestern U.S. is critically dependent on so-called “dryline” conditions where sharp gradients in soil moisture are present.

Thus, it is apparent that, in certain conditions, land memory in the form of the soil-moisture store, perhaps reinforced by positive feedback mechanisms such as recycling of precipitation, has significant effects on atmospheric variability and predictability and can lead to greater persistence of weather and climate anomalies. Delineation of the conditions under which soil-moisture state is important to the evolution of weather and climate, coupled with ways of estimating the initial soil-moisture state based on in situ and satellite observations and the realistic simulation of the subsequent evolution of that soil-moisture state in predictive models, should allow the extension of atmospheric forecast skills.

Among the predictability questions associated with soil moisture that will be addressed under GAPP are the following:

1. When operating in an uncoupled mode with observed (as opposed to modeled) precipitation, can the soil-vegetation-atmosphere transfer schemes used in climate prediction models adequately represent the observed seasonal evolution of soil moisture (and associated variables such as surface temperature) at catchment and regional scales in the GAPP study area? Furthermore, when coupled to horizontal routing schemes, can these models correctly simulate the hydrological response of catchments?

2. Does the use of off-line calculations of soil moisture improve predictions of regional seasonal climate and hydrological responses in the GAPP study area?

3. Are there ways of estimating the initial soil-moisture state in GAPP's regional hydrometeorological models based on in situ and satellite observations at catchment and regional scales, and does the use of such initialization methods improve the ability of these models to predict regional climate and hydrological responses in the GAPP study area?

4.2.4 Vegetation and Land Cover Dynamics

Vegetation plays a major role in determining the surface energy partition and the removal of moisture from the soil by transpiration. Representation of the vegetation's response (i.e., the change in live biomass) to atmospheric and hydrologic influences is currently weak in models used to give monthly to seasonal predictions of precipitation and hydrologic variables. GAPP should undertake research to better represent heterogeneous vegetation covers in models and to represent the seasonal evolution of vegetation.

There has been substantial progress in representing heterogeneous vegetation by specifying area average parameters on two fronts, one being essentially empirical and the other theoretical. The empirical approach (e.g., Mason, 1988; Blyth, et al., 1993; Noilhan and Lacarrere, 1995; Arain et al., 1996, 1997) is to create a coupled surface-atmosphere model, and to postulate and test hypothetical rules (often called "aggregation rules", Shuttleworth, 1991) that give parameters applicable at larger scales by combining the parameters that control surface exchanges for small plots of uniform land cover. The theoretical approach (e.g. l'Homme, 1992; McNaughton, 1994; Raupach, 1995; and Raupach and Finnigan, 1995, 1997) is to adopt the equations that are accepted as reasonable descriptions of land-atmosphere exchanges for small plots of uniform land cover and to assume that such equations can also be used to describe the area-average behavior of heterogeneous cover, and to derive theoretical equations that link the parameters required at large scales with those that apply for individual small plots. Ongoing research under GCIP is investigating the sensitivity of model predictions to improved representation of heterogeneous vegetation cover. GAPP will address the requirement to extend such studies into new areas of the U.S.A.

Most meteorological models either prescribe a seasonal evolution in vegetation parameters or assume that they are constant. Assimilating satellite observations is one way to provide a more realistic representation of current vegetation status in model simulations, and there is now great opportunity to develop this approach with data from the recently launched Earth Observing System. However, when using this approach, care is needed to avoid creating inconsistencies between the space-time distribution of soil moisture and the assimilated vegetation biomass growth pattern.

The assimilation of satellite data is appropriate in weather forecasting applications, and it is an excellent approach for studying model mechanisms, for providing fields for model initialization, and for documenting the regional vegetation "climatology". However, it is less appropriate in the context of freestanding, monthly to seasonal climate prediction models. In this case, the alternative approaches are (a) to impose prescribed seasonal patterns of the evolution of vegetation based on the previously observed cycle of vegetation climatology, or (b) to incorporate the growth and senescence of vegetation in an interactive vegetation model. This last approach would provide a tool for addressing the land memory aspects of vegetation.

Incorporating dynamic vegetation into a land-surface model is a relatively new innovation, but research in this area has already provided important insights. Claussen (1995), for instance, used an interactively coupled global atmosphere-biome model to assess the dynamics of deserts and drought in the Sahel. He found that the comparison of atmospheric states associated with these equilibria corroborates Charney's (1975) hypothesis that deserts may, in part, be self-inducing through albedo enhancement. Ji (1995) developed a climate-vegetation interaction model to simulate the seasonal variations of biomass, carbon dioxide, energy, and water fluxes for temperate forest ecosystems in northeastern China. Foley et al. (1998) directly coupled the GENESIS GCM and IBIS Dynamic Global Vegetation Model through a common treatment of land-surface and ecophysiological processes. They found that the atmospheric portion of the model correctly simulates the basic zonal distribution of temperature and precipitation (albeit with several important regional biases) and that the biogeographic vegetation model was able to capture the general placement of forests and grasslands reasonably well.

An interactive canopy model (Dickinson et al., 1998) has been added to the Biosphere-Atmosphere Transfer Scheme (BATS: Dickinson et al., 1986, 1993) to describe the seasonal evolution in leaf area needed in atmospheric models and to estimate carbon fluxes and net primary productivity. This scheme differs from that used in other studies by focusing on short time-scale leaf dynamics. Tsvetsinskaya (1999) introduced daily crop growth and development functions into BATS and coupled it to the National Center for Atmospheric Research (NCAR) Regional Climate Model to simulate the effect of seasonal crop development and growth on the atmosphere-land-surface heat, moisture, and momentum exchange. She found that the coupled model was in better agreement with observations than the earlier non-interactive mode. Lu et al. (1999) developed and implemented a coupled RAMS/CENTURY modeling system and, in the context of GCIP, successfully applied it in the central U.S. to study the two-way interactions between the atmosphere and land surface at seasonal-to-interannual time scales (Lu, 1999). All these early attempts suggest the value of including two-way feedbacks between the atmosphere and biosphere in meteorological models to create the soil-vegetation-atmosphere transfer schemes (SVATS) with “dynamic Vegetation” (IV), hereafter called IV-SVATS.

Among the predictability questions associated with seasonally changing vegetation cover that will be addressed under GAPP are as follows.

1. How can the representation of the dynamic biophysical properties of vegetation and heterogeneous land cover be improved and validated in predictive models?

2. Do currently available SVATS with vegetation dynamics realistically simulate the seasonal cycle of vegetation growth and senescence in the several ecohydrological regions present in the GAPP study area?

3. Assuming that IV-SVATS do give realistic simulation, does their introduction into GAPP’s regional coupled models improve the simulation of climate variables in the GAPP study area at catchment to regional length-scales and at time-scales up to seasonal?

4. How does the simulation of IV-SVATS into GAPP’s regional models influence the modeled relative contribution to precipitation of advected moisture relative to the contribution from local evapotranspiration, and how does it influence the relative importance with respect to predictability of precipitation arising from sea surface temperature anomalies and land-memory processes?

5. OROGRAPHIC EFFECTS

5.1 Rationale

The Western Cordillera imposes pronounced surface influences upon North American weather. These mountains determine locations of lee cyclogeneses in winter and spring; the associated elevated heat source anchors the summer monsoon; the deflecting effects channel moisture corridors and low-level jets; and the upwind slopes that are favored sites for winter snow packs contribute runoff to North American rivers.

Although many orographic influences represent semi-regular, and therefore potentially predictable elements of the seasonal cycle, it is necessary to quantify contributions of local and remote thermal and dynamic effects in order to advance simulations of related circulation patterns, precipitation, and land hydrology. Some climate elements, such as the North American monsoon are probably dominated by regional distributions of surface and latent heating. Other components, including the winter Rockies anticyclone must also be strongly modulated by mechanical deflection. Both thermal and dynamic effects influence the transition seasons of fall and spring, but their relative magnitudes remain to be determined.

Winter and transition season events are particularly important for the hydrology of the central and northern sections of the Cordillera. Unlike most other monsoonal areas of the world, it is the winter and transition seasons that provide most of the precipitation of this region. In view of this seasonal distribution, the present chapter places greater emphasis upon the winter and spring seasons when most of the mountain snow-pack develops and melts.

5.2 Scientific Background in relation to atmospheric circulation and precipitation variability

5.2.1 Large-Scales

Paegle et al (1987) show a regular phase-locking of monthly averaged lower-tropospheric circulations in western North America. Observed deviations from the monthly averaged climatology are strongly impacted by orography. Mo et al. (1995) suggest that the anomalously wet Mississippi Basin pattern of summer 1993 was due to unusually strong and persistent westerly currents over the Rocky mountains. The anomalous westerlies produced a topographic response similar to the observed anomaly in a simplified model. Pan et al (1999) demonstrate the important role of quasi-stationary, monthly averaged anomalies to both the lee-side LLJs and associated precipitation anomalies simulated in a relatively complete model for the1988 drought and 1993 flood.

It is reasonable to suppose that the orography plays an important role in the seasonal evolution of the climatology. The relative roles of different anchoring mechanisms, have, however never been clearly quantified. The mechanical blocking effect of topography produces an anticyclone above the highest mountains for strong westerly flow (Charney and Devore, 1979, Nogues-Paegle, 1979) and a cyclone in this location during weaker westerlies. This pattern is broadly consistent with lower tropospheric circulation changes from winter to spring (Paegle et al., 1987), although the circulation centers are not positioned over the highest orography in either season.

There is much evidence for strong local thermal forcing, particularly in summer when the western Cordillera forms a heated, elevated plateau (e.g. Smith et al., 1997). This mechanism is likely to be less relevant in winter. Some studies also suggest linkage of seasonal North American circulation re-arrangements to regional re-arrangements of tropical latent heating of the Amazon Basin and the eastern Pacific (Paegle et al., 1987) and for remote linkages of Asian Monsoon anomalies with North American monsoon anomalies (Lau and Weng, 2000). The possible relevance of several local and remote dynamic and thermal influences upon the climatology underlines the complexity of the forecast problem. High research priority should be placed upon diagnostic and prognostic studies designed to sort out the relative effects in different seasons.

Perspectives gained from vorticity dynamics can be particularly illuminating. In the presence of mountains, barotropic models that are founded upon the principle of vorticity or potential vorticity conservation are capable of explaining a substantial portion of the large-scale seasonal rearrangements. These models have been used to describe the scale dependence of topographic influences as well as lee-side flow characteristics. Charney and DeVore (1979) and Nogues-Paegle (1979) point out abrupt reversals of relative vorticity that may occur when the zonal flow fluctuates about near-resonant values for stationary, orographically forced Rossby waves.

5.2.2 Local-Scales

Major gaps remain in our understanding of the natural evolution of clouds and precipitation in mountainous terrain, especially at horizontal scales less than 100 km. Most measurements of air motions over complex orography (Neff, 1990) lack the spatial resolution to identify small-scale features like gravity waves, barrier jets, cold air pools, convergence zones, channel and blocked flows. These phenomena interact with cloud and precipitation development above the western Cordillera. Atmospheric stability also plays an important role. In winter the atmosphere is generally stable during pre-frontal periods and becomes less stable after the front passes. Stably-stratified flows excite waves that interact with cloud and precipitation development, whereas post-frontal periods are dominated by convective clouds that also interact with the orographic flow. A portion of the energy associated with these disturbances radiates away from the mountains as transient gravity waves, while some of the response may be orographically-bound in a semi-steady state.

Enhanced vertical motions resulting from low level lifting of air by orographic barriers that further excites gravity waves, often lead to the development of clouds and precipitation. Gravity waves can penetrate through deep layers and significantly influence the location, intensity, and microphysics of precipitation reaching the surface. Little effort has been directed towards understanding the effect of gravity waves on cloud and precipitation development. As a result, the interactions between air motions, cloud, and precipitation development on the smaller scales (10 to 100 km) is still poorly understood. When mountain waves induce cloud development, the clouds can modify the thermodynamic profile of the atmosphere and in turn the gravity wave structure. For example, condensation reduces atmospheric stability, thus decreasing gravity wave frequency; i.e. increasing the vertical wavelength of mountain waves (Barcilon et al., 1979; Durran, 1990). For flow over complex terrain, the combined effect of these mechanisms is still poorly understood.

Smith (1979) and Cotton and Anthes (1989) provide detailed reviews of wintertime orographic flows and precipitation. Although numerical models have demonstrated an ability to provide realistic simulations of certain mesoscale flows and weather systems (Cotton and Anthes 1989), an accurate prediction of the amount and, to a lesser extent, the location of precipitation in mountainous regions has remained an elusive goal. Mesoscale convective systems occur in the lee of the Rockies and commonly provoke severe weather and flash floods there during spring and summer. It has been suggested (Tripoli and Cottion 1989a,b) that these systems are accompanied by thermally driven solenoidal circulations and that their development is favored over the Rockies. The mountain/plains solenoidal circulation has been implicated in the formation of long-lived mesoscale convective complexes over the central United States (Davis and Weissman, 1994; Olsson and Cotton, 1997a,b). These weather elements also interact with the leeside, Great Plains low-level jet, particularly during the night when the jet and leeside convection both reach maximum strength (e.g. Nicolini et al., 1993).

5.2.3 Role of Coupled Land Surface-Atmosphere-Ocean Interactions

Some seasonal anomalies of precipitation appear to be connected to ENSO fluctutations. Cayan et al (2000) studied a group of La Nina and El Nino years for the period of 1949-1995. They conclude that over the U.S. Southwest, mildly wet days are more frequent in typical El Nino years and very wet days are even more frequent in such years. They also find that higher streamflow values are much more frequent in typical El Nino years and conclude that streamflow patterns are accentuated replica of precipitation patterns. The pattern over the Pacific Northwest and northern Rockies shows a reverse correlation with El Nino. Here mildly wet days are less frequent in typical El Nino years and very wet days are even less frequent during El Nino years. High streamflow values are much less frequent in this portion of the Rockies during El Nino events.

The local streamflow signal is strongly reflective of ENSO related atmospheric anomalies, but less clear for those rivers that have important tributaries over a broad latitude belt. For example, the Green river tributary of the Colorado river originates in the northern Rockies and may correlate with dry El Nino episodes, while lower-latitude tributaries of the Colorado are wetter during El Nino and this trend tends to weaken the net ENSO signal.

5.2.4 Role of Inland Surface Variability

While orographic uplift provides the major surface forcing of precipitation on the western sides of mountains, other surface mechanisms are also locally important. The Great Salt Lake, for example, appears to enhance cold-season precipitation to its lee. The lake effect is difficult to distinguish from local topographic uplift in observations, but model studies (Onton, 2000) clearly point to a lake influence in pronounced events. The Great Salt Lake depth increased by about 10 feet from an average prior depth of about 10 feet, and horizontal area increased substantially after an unusually wet period in the early 1980's. The lake covered an even larger area and was several hundred feet deep approximately 18,000 years ago when it was refered to as Lake Bonneville and spanned much of present-day Utah, eastern Nevada, and southern Idaho.

This largest inland body of water of the western United States has strong surface interactions with climate variations and contribute to the water cycle of the semi-arid west and presents potential hazards to local development. During its modern recorded maximum of the mid-1980s, the lake inundated portions of interstate highway 80, the major east-west land route through the Central Rockies, and its surface elevation was within 1 foot of the lowest runways of the largest airport of the Great Basin.
Onton (2000) demonstrates that the dominant lake effect on lee-side snow bands is surface buoyancy enhancement, and evaporation from the lake is secondary. A thermodynamically similar influence may be noted over extensive moist salt flats located west of the lake. These salt flats retard surface drying because of the reduced saturation vapor pressure of salty brines and reduce surface temperature response because of the high conductivity and heat capacity of wet soils. Large differences of skin

temperature have been noted between wet salt flats and adjacent regions of dry soil. These surface variations are usually neglected in models, and neither the Great Salt Lake, nor the surrounding mountain ranges, are adequately resolved by most models, particularly in climate simulations. Both topography and these other surface variabilities affect simulated mesoscale circulations (Astling, 1990), and their inadequate resolution may contribute to the relative minimum of forecast accuracy of precipitation over the central Rockies found by Gartner et al. (1996) and by MacDonald (1998) in operational forecast models.

5.2.5 Role of Maritime Mountains

The mountainous coastal zone of the western United States has experienced several prolific flooding events in the past decade, resulting in more than 6 billion dollars of damage and loss of dozens of lives (Colle and Mass, 2000). Recent events occurred in California during winter 1994-95 when flooding in the Russian River basin produced $800M dollars of damage; over the Pacific Northwest in February 2000 when the Columbia and Willamette Rivers crested 10-20 feet above flood stage (Colle and Mass 2000) and during the 1997-98 El Nino, when floods, landslides, and agricultural damage due to heavy precipitation produced losses totalling $1.1 billion (Changon 1999).

Such events involve significant interactions between large-scale atmospheric flow anomalies, orographic precipitation enhancement, and surface hydrology effects. For example, extreme flooding events over the Pacific Northwest are most common during the fall and are frequently preceeded by heavy snows that reach unusually low elevations (e.g. Colle and Mass 2000). The subsequent development of moist southwesterly large-scale flow with connections to the subtropics, known colloquially as the "pineapple express", results in rapidly melting snowpack as the snow line retreats to higher elevations, and heavy precipitation. Due to high freezing levels, orographically enhanced precipitation over the Coast Range and Cascade Mountains falls predominantly as rain. During the 5-9 February 2000 flooding event, liquid precipitation in the lower and higher elevation regions of the Pacific Northwest ranged from 10-25 and 35-75 cm, respectively. High freezing levels further augmented this rainfall with 10-

30 cm of water equivalent snowmelt (Colle and Mass 2000). Flooding events in California can feature rainfall rates over mountainous terrain of as much as 25 cm/day.

5.2.6 Role of Microphysical Processes

A correlation exists between the temporal and spatial evolution of clouds and the complexity of the terrain (Rauber et al., 1986; Rauber and Grant, 1986; Marwitz, 1986; Deshler et al., 1990; Huggins and Sassen, 1990; Super and Holroyd, 1989; Super et al., 1989). Marwitz (1986) compared cloud and precipitation evolution in winter orographic clouds over the Sierra Nevada and San Juan mountains and found significant differences in flow dynamics and microphysical processes between the two mountain ranges.

Understanding microphysical processes and their complex interactions with the dynamics in winter storms in mountainous regions can be substantially increased using numerical models, especially when supported by field measurements. Such modeling studies enhance understanding of the roles of various microphysical processes on heat and moisture budgets of clouds and their role on precipitation development.
Several levels of cloud microphysical treatment have been attempted, but it is not yet clear how detailed these calculations must be to provide acceptable simulations of cloud processes and quantitative precipitation forecasting. Gaudet and Cotton (1998) showed significant improvement in precipitation skill with the use of bulk microphysics. However, the simulations produced excessive precipitation at low-levels and too little at higher elevations. In addition, systematic biases have also been found in real-time simulations with the MM5 in the Cascades producing too much precipitation on the windward side and too little on the lee side (Colle et al., 1999). This bias also occurred in the 10 km Eta model (Colle et al., 1999). These biases may be related to specifications of microphysical processes in the parameterizations. Important parameters found to be sensitive to the development of precipitation are, for example, fall speeds of hydrometeors and the definition of the cloud droplet spectra. Interaction of the dynamics with microphyscal processes may also play a role.

5.3 Objectives

The central goal of orographically oriented GAPP studies is to improve predictive capability from monthly to seasonal ranges for precipitation and surface hydrology in the vicinity of the western Cordillera. The specific steps include:

1) Quantify regional and remote surface processes that determine the regular annual cycle in the vicinity of the Rocky mountains
2) Examine predictability of the average seasonal cycle and of anomalies from the average.
3) Explore model methodologies required to simultaneously resolve global to local catchment scales.

These goals will emphasize the winter and transition seasons to complement NAMS objectives outlined in Chapter 6.

5.4 Scientific Approach

The above stated objectives will be addressed by building on collaborative research and through the new initiatives outlined below.

5.4.1 Collaboration with other projects

The relatively well-defined forcing of mountains helps to simplify the dynamics, particularly in the case of stable witnertime flows. Such winter storms present a broad range of active microphysical processes and as such provide a fixed natural "laboratory" for studying the dynamics and microphysics of cloud systems (Banta, 1990). These concepts have motivated a number of scientific studies and field programs. Recent field programs include the Arizona Program (Klimowski et al., 1998; Bruintjes et al., 1994), COAST (Bond et al., 1997), CAL-JET (Ralph et al., 1998), and MAP (Houze et al., 1998) which focused on precipitation in the Alps. These programs mainly emphasized orographic surface forcing interacting with cloud dynamics, but other surface forcings associated with lakes and variable soil moisture are also relevant in certain regions of western North America.

The Intermountain Precipitation Experiment (IPEX) took place in February 2000 and was centered over the Great Basin (Steenburgh, 2000). This experiment was partly motivated by the observation that the Eta model Quantitative Precipitation Forecast

(QPF) skill is lower over the Intermountain West and eastern Rocky Mountains than over any other region of the U.S. (Gartner et al., 1996). Its base of operations was selected in part by the need to distinguish the surface roles of topography and lake effects upon precipitation in the Central Great Basin and partly by the proximity of an extensive mesonet of surface-based stations (Horel, 2000). This experiment and MAP place an emphasis upon cloud microphysics thought to be important on small scales characterizing highly corrugated local topography.

5.4.2 Identification of sources of seasonal cycles

GAPP will promote studies designed to explain what determines the annual cycle over North America as well as deviations from that cycle. Since the possible surface forcings span a broad range of local and remote thermal and dynamical effects it is impractical to address this problem through field programs of limited duration and areal coverage. These studies will consequently have heavy reliance on models.

The relative contributions of dynamic and thermodynamic orographic effects require further quantification. Important elements of summer to winter variability are present in global models of relatively low resolution (e. g. Nogues-Paegle et al., 1998). Such models may be used in inexpensive configurations to study local and remote surface forcing of the semi-stationary wave patterns characterizing the climatology of each season. If dynamic effects dominate the winter-time orographic influence implied in earlier discussions of the upper left panel of Fig. 5.1, the west coast anticyclone should be largely unaffected by the presence or absence of surface heat flux over the Rockies, but depend essentially upon the presence of this mountain range. A series of experiments can be designed to address this question, and their results will have obvious relevance to explanations of the seasonal evolution and form the basis for understanding deviations from this evolution.

5.4.3 Identification of sources of anomalies and precipitation predictability

Precipitation prediction is among the most difficult forecasting problems and even with vastly improved observations and numerical models in recent times, skill in precipitation forecasting has been improving very slowly (Fritsch et al., 1998). Olsen et al. (1995)

show that prognostic skill levels for heavy precipitation events are highest in the winter, and attribute this to the larger-scale character of cold season precipitation events.
The role of topographic organization of precipitation is more difficult to evaluate. Gartner et al. (1996) demonstrate that the highest equitable threat scores over the conterminous U. S.A. for the meso-Eta model are found around the West Coast, although there is an extensive data-sparse region to the west. One possible explanation for this skill enhancement may be orographic organization of precipitation and related predictability enhancement. This explanation would also imply relatively high skill scores over the central and eastern Rockies, but Gartner et al. (1996) find that here the meso-Eta model has relatively low skill.

In some respects, the problem of monthly and seasonal precipitation prediction may be simplified by the averaging inherent at these extended ranges. Precipitation outlooks accompanying the last strong El Nino were remarkably good. However, neither the ENSO signal, nor the prospects for predictability enhancement, were always regarded as useful elements to extra-tropical prediction. Indeed, the observed extra-tropical ENSO signal is quite variable. For example, the weak warm event of 1976-1977 was marked by substantial winter drought over most of the West, while strong warm events of 1992-1993 and 1997-1998 were accompanied by serious flooding. Earlier model studies emphasized the role of natural variability and the difficulty in sorting out ENSO related signals at higher latitudes (e.g. Geisler et al., 1985). Estimates of predictability based on model simulated signal and noise gave generally pessimistic views about the prospects for dynamical seasonal prediction in mid-latitudes (Chervin, 1986). Efforts at deterministic extended range prediction (Miyakoda et al, 1983, 1986) displayed feasibility of monthly dynamical prediction, but it was realized that the deterministic predictability of the first ten days was the basis of dynamical predictability of the monthly mean. This fact led to further skepticism regarding extended range predictability.

Many earlier models did not produce realistic extra-tropical height anomalies in relation to tropical SST anomalies (review by Lau, 1997). More recent modeling efforts (e.g. Shukla et al, 1999) display much higher skill in seasonal prediction of the Pacific-

North American flow anomalies in the presence of large tropical SST anomalies. The skill enhancement is presumably related to model improvements and it is reasonable to postulate that continued model advances should allow further predictive improvements. This supposition forms the working hypothesis for GAPP, and available evidence suggests that the winter and transition seasons may be especially well suited for its exploitation. The GAPP research community can both benefit from past model advances and contribute to model evolution, as outlined below.

5.4.4 Explore and Develop Model Methodology

Many of the requisite model developments are similar to those addressed in the earlier modeling sub-section on monsoons and summer precipitation. In view of the monthly to seasonal forecast requirement, it is necessary to include global forecast capability. In addition, the relatively poor meso-Eta model precipitation forecasts at 29 km resolution over the extreme topography of the central Rockies (Gartner et al., 1996) suggest a need for exploratory forecasts at much higher resolution. Such simulations may require non-hydrostatic treatment and prognostic cloud microphysics.

The optimal model configuration would contain all necessary features in a global, variable resolution treatment or global model with two-way interactive high resolution nests that can focus on a number of watershed catchments. This capacity is currently available only in early developmental stages, particularly for versions that include non-hydrostatic dynamics and prognostic cloud microphysics in a fully global treatment. Real-time three-dimensional prototype regional/mesoscale precipitation prediction studies for Colorado have been conducted for more than six years (Cotton et al., 1994). These simulations used the CSU RAMS with bulk microphysics (Walko et al, 1995) at horizontal grid resolutions between 16 and 80 km. More recently Bruintjes et al. (1994) completed research simulations of heavy precipitation events with horizontal grids as fine as 2 km. These simulations also used bulk microphysics and non-hydrostatic dynamics with interactive grid-nesting. Good correlation between model precipitation dynamics and observations were obtained. The results indicated that a seeder-feeder mechanism enhanced precipitation that contributed to flash flooding. Accurate simulation of gravity wave-cloud interactions and precipitation development required horizontal grids of 2 km.

It is important to know the spatial and temporal variations of aerosol and CCN concentrations as they affect microphysical processes of precipitation development in clouds. Studies including aerosol and CCN as field variables in microphysical parameterizations in numerical models are necessary. This approach may eventually allow dynamic adjustment of the microphysical parameterization to differing aerosol and CCN characteristics and could produce a more robust model and reduce the need for tuning parameterization with changes in airmass. In addition, investigations are needed to determine whether parameterizations based on a number of well-tuned case studies provide robust solutions that capture natural precipitation phenomena in a consistent manner.

6.0 NORTH AMERICAN MONSOONAL CIRCULATIONS

6.1 Rationale

A fundamental and necessary first step towards improving warm season precipitation prediction over the United States is the clear documentation of the major elements of the warm season precipitation regime and its variability within the context of the evolving land surface-atmosphere-ocean annual cycle. Monsoon circulation systems, which develop over low-latitude continental regions in response to seasonal changes in the thermal contrast between the continent and adjacent oceanic regions, are a major component of continental warm season precipitation regimes.

6.2 Scientific Background

The North American warm season is characterized by a monsoon system [hereafter referred to as the North American monsoon system or NAMS] that provides a useful framework for describing and diagnosing warm-season climate controls and the nature and causes of year-to- year variability. A number of studies during the past decade have revealed the major elements of the NAMS, including its mean seasonal evolution and interannual variability. Its broadscale features and variability are described together with a literature review in Appendix A.

The NAMS displays many similarities (as well as differences) with other regional monsoons, most notably the southern and eastern Asian monsoon complex and the Australian and West African Monsoons. While the NAMS is less impressive than its cousins, it still has a tremendous impact on local climate. Of significance to GAPP is the fact that the NAMS affects much of the USA, and in particular one of the new GAPP large-scale study areas. Notable features of the NAMS include major low-level inflow of moisture to the continent, a seasonal increase in continental precipitation and a relatively warm troposphere over the monsoon region resulting in a “monsoon high” in the upper troposphere. There are also significant regional differences that arise as a result of coastal geometry, topography and latitudinal distribution of the continents.

6.2.1 North American Warm Season Precipitation regimen

There are fundamental differences between the North American cold season and warm season precipitation regimes. The upper tropospheric mid-latitude westerlies are much weaker during the warm season, as are the extratropical storm tracks, which shift poleward to a mean position near the US-Canadian border. In the eastern tropical Pacific the ITCZ and equatorial cold tongue intensify as the huge Americas sector tropical precipitation maximum shifts from Amazonia to the eastern Pacific - central American region. To the north, there is clear evidence of increased continental-scale controls of the precipitation regime over the U.S. and Mexico. The energy at smaller spatial scales increases (e.g. terrain related diurnal variability and convective precipitation related to terrain and coastline features), and much of the continent becomes an atmospheric moisture source, i.e. evaporation exceeds precipitation.

Precipitation is an intermittent process. Individual precipitation events occur in association with synoptic, diurnal, and mesoscale atmospheric circulation systems. The number and / or intensity of these events over a month or season can vary substantially from year to year. Part of this time-averaged variability appears to be a response to subtle variations in the distribution of tropical sea surface temperatures (SSTs), but the mid-latitude response to these tropical anomalies is regionally and seasonally dependent. There is also persuasive evidence that variations in land surface conditions, particularly soil moisture and vegetation, can also play a significant role in warm season precipitation variability, including over mid-latitude continental-scale areas. While the typical ocean memory time-scale is longer than that of soil moisture, both memory components of the climate system are of importance for seasonal-to-interannual climate prediction.

6.2.2 Role of Coupled Land Surface-Atmosphere-Ocean Interactions

The land and ocean surface memory components of the climate system evolve more slowly than the individual precipitation-producing circulation systems and are to some degree predictable in their own right (see Appendix A). This fact, together with other recent advances in the monitoring and modeling of ENSO-precipitation relationships and in the diagnosis and understanding of the role of land surface processes in the continental hydrologic cycle and of SST-forced atmospheric circulation anomalies, provides evidence that there is a deterministic element in the climate system which may be exploitable for prediction. Prospects for improved prediction on seasonal-to-interannual time scales hinge on the inherent predictability of the system and our ability to quantify the initial states and forecast the evolution of the surface forcing variables (i.e. SST, vegetation and soil moisture).

It is important to recognize that, depending on the variable and the time of the year, the evolution of particular surface forcing variables may not be slow. For example, in western Mexico the vegetation type and fractional vegetation coverage changes dramatically in just a few weeks during the onset of the summer monsoon. Observations from the Oklahoma Mesonet indicate that soil moisture can change dramatically with one heavy rainfall event.

The relative importance of the land and ocean influences on North American precipitation changes with the seasons. The influence of tropical SST anomalies on North American climate is strongest during the cold season, but warm season correlations between SST and continental-scale rainfall are at least marginal. In contrast, the influence of the land surface is strongest during the warm season, when the continents are warmer than the surrounding oceans and surface evaporation is large and varies greatly as a function of terrain and vegetative cover. It should be noted that the influence of SST anomalies on cold season precipitation can indirectly affect warm season rainfall, since they play a role in determining the initial springtime soil moisture conditions and vegetative cover, which in turn can feed back upon the climate during the warm months through their influence on surface air temperature and evaporation.

Prediction of the detailed regional distribution of continental precipitation is a challenging task since it requires the skillful modeling of the subtle interplay between land surface and oceanic influences such as the complicating influences of terrain and coastal geometry. While resolution of global models continues to increase with enhancements in computational capability, there is currently a need for higher resolution regional mesoscale models and multi-year assimilated data sets.

6.2.3 Role of low-level jets

The Great Plains low-level jet (GPLLJ) plays a critical role in the summer precipitation and hydrology of the central US. Though less extensive, the Gulf of California low-level jet (GCLLJ) contributes to the summer precipitation and hydrology in the southwestern US. Developing a better understanding of both of these jets is of critical importance to GAPP.

The GPLLJ transports considerable moisture from the Gulf of Mexico and eastern Mexico into the central US. It is controlled by large-scale dynamics, the strength and size of the energy sources over the Gulf of Mexico and the InterAmerica Sea, and land surface effects, including vertical motion induced by topography, elevated heat source and dynamic effects over the Rocky Mountains, radiation balances on the land, and temperature contrasts between the land and the Gulf of Mexico. The diabatic effects of land in this regional circulation must be understood and modeled. For example, nocturnal dynamic and thermodynamic factors may be mutually reinforcing, thus contributing to the strength of the moisture convergence into the Mississippi River Basin during the night and early morning.

The Gulf of California jet transports low-level moisture from the eastern tropical Pacific towards the southwestern U.S. It is inextricably linked to tropical easterly waves and Gulf surge events that play a critical role in the intraseasonal variability of the monsoon along the west coast of Mexico and in the desert Southwest. Most of the moisture in the lower troposphere (below 850-hPa) over the southwestern US (west of the continental divide) arrives with the GCLLJ, while most of the moisture at higher levels arrives from over the Gulf of Mexico. Difficulties in explaining the observed precipitation distribution and its timing, have been due, in part, to the fact that Baja California and the Gulf of California have not been properly resolved in the past. Recently there has been considerable progress in diagnosing and modeling the regional circulations that contribute moisture to the core region of the North American monsoon, including the diurnal cycle, which must be properly represented to capture the interactions between the circulation and precipitation (see Appendix A, section A.1).

6.3 Objectives

The goal of GAPP studies of the NAMS is to determine the degree of predictability of warm season precipitation and surface air temperature over North America, with emphasis on the role of the land surface boundary forcing on time scales ranging up to seasonal and interannual. The studies will address three major objectives:

1. Describe, explain, and model the summer climate regime and its associated hydrologic cycle in the context of the evolving land surface-atmosphere-ocean annual cycle.
2. Describe, explain, and model warm season precipitation and temperature variability with emphasis on seasonal-to-interannual time scales.
3. Describe, explain, and model the spatial variability of summertime precipitation on the mesoscale to the continental scale.

While the role of the land surface component of the boundary forcing is emphasized, the relative roles of the land surface and ocean surface forcing is necessarily a major issue. Thus, much of the work on monsoonal circulations will be advanced through collaboration with the CLIVAR/VAMOS program and the CLIVAR/PACS-GEWEX/GCIP North American Warm Season Precipitation Initiative. During the later stages of GAPP, the efforts of the monsoonal circulation and land memory research will contribute to a GAPP seasonal prediction effort involving high-resolution global models.

6.4 Scientific Approach

The three objectives discussed in Section 6.3 will be addressed by a symbiotic mix of diagnostic and modeling studies whose integrated thrust can be broadly characterized as "the role of the land surface in warm season precipitation predictability over North America". Diagnostic studies will provide an improved description and understanding of the nature and variability of the NAMS, especially in the vicinity of the GAPP large-scale study areas. This study includes the identification of spatially and temporally coherent relationships that have implications for prediction and need to be further explained through subsequent model experiments. Other GAPP related investigations of the land surface will provide initial and boundary conditions and validation for model experiments and guidance as well as hypotheses for the design of these experiments. Conversely, the model experiments will provide a deeper understanding of dynamic and thermodynamic processes and thus allow a broader interpretation of the empirical results. Highly focused field activities of limited temporal / spatial extent will be undertaken in concert with other components of GAPP.

6.4.1 Diagnostic Studies

GAPP diagnostic studies will focus on the description and understanding of the evolutionary aspects of the NAMS, especially as it relates to the land surface. Feedbacks between the land and atmosphere arising from terrain, soil moisture conditions, vegetation, snow cover and groundwater, and their effects on future states of the atmosphere will be emphasized. These studies will constitute a multi-scale approach in both space and time. The temporal resolution will vary, but will usually not exceed one month. In some cases the studies will be “event oriented”, i.e. studies “indexed” to the life cycles of specific hydrologic anomaly events. As a consequence, the spatial domain of these studies will necessarily range from regional to planetary. Some studies will require a full latitude perspective over the North American sector, from the ITCZ to at least the middle latitude storm track. These studies will be carried out in tandem with land surface model experiments and land data assimilation experiments and will benefit from multi-year regional reanalyses and retrospective soil moisture analyses carried out under other components of GAPP.

Three principal scientific questions will be addressed

1. How is the evolution of the warm season (May-October) atmospheric circulation and precipitation regimes over North America related to the seasonal evolution of the land surface boundary conditions?

These studies will require an improved characterization or “indexing” of the seasonal evolution of soil moisture and vegetative cover over the entire North American continent, and a higher resolution climatology over the GAPP large-scale study areas. These studies presume that the general nature of the warm season evolution of the atmospheric circulation and precipitation regimes over North America is reasonably well known from previous studies, although there are still many aspects of mesoscale systems where our understadning needs to be improved.

2. What are the interrelationships between year-to-year variations in warm season land boundary conditions, the atmospheric circulation and the continental hydrologic regime?

These studies are essentially diagnostic that will initially focus on the search for and / or better understanding of spatial / temporal linkages between precipitation anomalies, circulation parameters and the boundary forcing parameters. Included are the determination of the role of tropical and extratropical transients in seasonal variability.

In addition to simple correlation studies, it will be important to develop methods for characterizing and categorizing extended hydrologic anomaly episodes in terms of their magnitude and space / time evolution and indexing such episodes to the variability and seasonal evolution of the NAMS and land surface forcing fields. These studies will be structured to identify and quantify feedbacks between the land surface boundary forcing and the atmospheric circulation for subsequent modeling and predictability studies.

3. What are the significant features of and interrelationships between the anomaly-sustaining atmospheric circulation and the land surface boundary conditions that characterize large-scale long lasting continental precipitation and temperature anomaly regimes during the warm season?

These studies will involve case studies of major 20th century hydrologic anomaly regimes over North America, with particular emphasis on the most recent events for which the best data and analyses are available (i.e. the 1988 late spring-early summer drought and subsequent "heat wave", the late 1993 summer flood regime over the upper Midwest, and subsequent large-scale summer anomaly regimes which might develop during the lifetime of GAPP). The emphasis will be on the seasonal-to-interannual time scale, but data limited studies of the more pronounced multi-year anomaly regimes of the past (e.g. the Midwestern drought regime of the 1950s) could be undertaken to better describe and understand the multi-year regimes on which the large-amplitude interannual variations are superimposed. These studies will necessarily rely on data sets produced by other components of the GAPP project, such as the regional reanalysis and retrospective soil moisture analysis.

6.4.2 Modeling

As part of its overall mission, GAPP will pursue the development of improved land surface and hydrologic models as well as improved land-atmosphere coupled models. With this fact in mind, the emphasis of modeling studies of the NAMS will be to (1) exploit rather than duplicate the model development activities of the other components of GAPP, and (2) undertake diagnostic and predictability studies of the NAMS that emphasize the regional-scale continental perspective of GAPP.

Apart from their use in operational prediction, models are excellent tools for testing hypotheses of predictability and establishing the sensitivity of predictions to surface boundary conditions. In regions where the surface forcing of the atmosphere varies on spatial scales of less than a few hundred kilometers, the current resolution of global climate models (GCMs) is inadequate to resolve the detailed variability required for application to water resource problems on the catchment scale. On the other hand, higher resolution regional mesoscale models (RMMs) cannot reflect the full planetary forcing, but can more accurately represent the effects of regional gradients associated with features such as coastlines, orography, land use, soil and vegetation type.

With the steady increase in computational power, it seems reasonable to expect the resolution of GCMs to ultimately reach that of current operational RMMs. Until then, both GCMs and RMMs will be needed for process studies of the land surface, ocean and atmosphere. At present, the embedding of RMMs into GCMs provides a method for handling the macroscale-mesoscale mismatch over a limited area of the earth. To date nested simulations have generally been limited to a one-way procedure (i.e. the RMM is driven by the GCM but there is no feedback to the GCM). Two way nesting procedures are necessary to allow feedback of the mesoscale variability onto the planetary scale circulation.

Predictability studies will be designed to identify the major physical components of the North American warm season precipitation regime that determine the quality of a prediction. This process includes (1) the role of land surface processes in seasonal variability, (2) the relative roles of land and ocean surface processes in seasonal variability, and (3) geographical, regime and variable field dependence of predictability. Since there is a large array of possible sensitivity experiments involving GCMs and RMMs in which different boundary and initial conditions are prescribed, these experiments must be carefully designed and selective in nature.

The multiple-scales challenge inherent in the modeling component of GAPP should extend beyond the forcing to consider the various spatial scales associated with precipitation itself. To meet this challenge, GAPP aims to

(i) understand/predict coarse-resolution precipitation fields generated by GCM's versus those generated by spatially averaging RMMs over the GAPP domain

(ii) understand/predict high-resolution fields generated at the native resolution of RMM's versus those produced by statistically downscaling GCM output (e.g. using a PRISM-style approach)

A comprehensive program of model simulations will be undertaken to demonstrate the level of skill in forecasting warm season precipitation anomalies. These studies will focus on hindcast simulations of carefully selected baseline hydrology anomaly regimes in which various modeling groups can participate. While initial experiments may use the NCEP/NCAR or ECMWF Reanalyses as the "observed data", multi-year assimilated data sets will become an integral part of the overall experiment design. Therefore, it will be necessary to assemble the best possible suite of data sets for the baseline periods to serve as the standard set of observations for these experiments.

Recently, NCEP launched the first phase of a regional reanalysis project. This project promises to produce outputs that will be important for assessing the role of large-scale processes, such as the effects of ocean forcing on the prediction of moisture bearing storm systems that affect the interior of North America. If this project proceeds on track, then the regional reanalysis products will be available for use by the GAPP investigators in 2002. Another source of regional information will be the Land Data Assimilation System (LDAS) currently under development by GCIP.

6.4.3 Field Programs

GAPP is currently planning field activities in two large-scale areas: the Southwest and the western Cordillera. The emphasis on the southwestern United States implies that GAPP studies of the NAMS will play a significant role in the planning and execution of the enhanced observing periods. Given the important role of the land surface in the evolution of the monsoon in this region, GAPP will pursue limited field studies of important surface parameters, such as vegetation biomass and soil moisture in these regions.

Studies of the GPLLJ will build on existing infrastructure in the region and possible enhancements will also serve as a contribution to the WCRP Coordinated Enhanced Observing Period (CEOP). A key facility will be the CART/ARM site where GCIP has installed a soil moisture network. Another nearby ongoing data source is the Walnut Creek watershed that has been instrumented by the Cooperative Atmosphere-Surface Exchange Study (CASES).

6.4.4 Data Set Development and Data Management

The multi-scale diagnostic and modeling studies of the NAMS will require a variety of basic data sets and data products, which we visualize will be distributed primarily from the established data distribution centers and through the data services of GAPP. NAMS diagnostic studies will rely heavily on operational analyses and satellite data products, and on global Four-dimensional Data Assimilation (4DDA) operational products, notably the output from the NCEP/NCAR Reanalysis, the ECMWF Reanalysis, the NCEP Regional Reanalysis, the Eta Model Data Assimilation System (EDAS) and the Land Data Assimilation System (LDAS). However, as previously noted, it will be necessary to assemble comprehensive data sets to be used in the analysis and modeling of "baseline" anomaly regime periods.

Where augmentation is required, it will be accomplished by an expansion of the data management activities of GAPP. For example, selected GAPP observational data sets may be expanded to full continental coverage or via special research efforts (e.g. construction of high resolution satellite data products). Of particular significance in this regard is the use of satellite data to construct an improved, high resolution description of land surface conditions and the development of high spatial and temporal resolution precipitation data sets over the continent and neighboring ocean regions.

*** Do we still have that mature phase (July) map for use in GAPP report?**

Figure 6.1. Mean (1968-1988) monthly 925-hPa vector wind (units: m/s), 200-hPa streamlines, and US_Mexico precipitation (shading) for (a) May, (b) June, (c) July and (d) August. Circulation data are from the NCEP/NCAR Reanalysis. A topography mask has been applied to the 925-hPa winds. Precipitation amounts are in mm/day and values greater than 1mm/day are shaded. The characteristic vector length is 10 m/s.

Figure 6.2. Moisture flux convergence during (a) daytime, (b) nighttime , (c) their difference and (d) daytime minus nighttime difference in moisture flux. Daytime is defined as 18-24 UTC (11 a.m.-5 p.m. local time). Nighttime is defined as 6-12 UTC (11 p.m.-5 a.m. local time). Contour intervals in (a)-(c) are 0.2 mm hour-1 and positive values are shaded. The standard vector length is 100 kg (m s)-1 and values smaller than 30 kg (m s)-1 are masked. (From Berbery 2000)

Figure 6.3. Top Left: Longitude-time diagram of the composite mean (1963-94) observed precipitation anomalies (departures from the JJA 1963-94 time mean) averaged between 34N and 38N. Results are shown for a 3-day running mean.

Top Right: Map of observed precipitation represented as the composite mean (1963-94) difference between the 45-day period after onset (day 0 to day +44) and the 45-day period before onset (day -45 to day -1). In previous two figures, the contour interval is 0.25 mm/day, the zero contour is omitted for clarity, and values greater than 0.25 mm/day (less than -0.25 mm/day) are shaded dark (light).

Bottom Left: Map of NCEP 200-hPa wind (units: m/s) and divergence (units: 1.0e-6/s). The contour interval is 0.5e-6/s.

Bottom Right: Map of NCEP 500-hPa vertical velocity (units: microbar/s) represented as the composite mean (1979-94) difference between the 45-day period after onset (day 0 to day +44) and the 45-day period before onset (day -45 to day -1). The contour interval is 0.05 microbar/s.

Figure 6.4. Composite evolution of the 30-day running mean area average precipitation (units: mm/day) over Arizona and New Mexico for wet monsoons (dotted line), dry monsoons (dot-dashed line) and all (1963-94) monsoons (solid line). The average date of monsoon onset is July 1 for wet monsoons, July 11 for dry monsoons and July 7 for all monsoons (defined as day 0 in each case).

Figure 6.5. Time-latitude sections of the mean (1961-1990) annual cycle of (a) precipitation, (b) maximum surface temperature, (c) minimum surface temperature, and (d) diurnal temperature range (i.e. the difference between (b) and (c)). Data are averaged zonally over West Coast land points at each latitude.

Figure 6.6. Conceptual model of the initiation and propagation of gulf surge events as suggested by Stensrud et al. (1997). Letter S denotes the area of surge initiation, with the diagonal arrow indicating the direction of surge propagation. The +/- indicate regions of upward / downward motion associated with the easterly wave trough, while the arrow indicates the direction of movement of the trough (from Fuller and Stensrud, 2000).

Figure 6.7. Composite evolution of MJO events during the summer months together with points of origin of tropical cyclones that developed into hurricanes / typhoons (open circles). The green (brown) shading roughly corresponds to regions where convection is favored (suppressed) as represented by 200-hPa velocity potential anomalies. Composites are based on 21 events over a 19 summer period. Hurricane track data is for the period JAS 1979-1997. Points of origin in each panel are for different storms. Contour interval is 0.5x106 m2 s-1, negative contours are dashed, and the zero contour is omitted for clarity.

Figure 6.8. Composite precipitation (mm day-1) for the control climate relative to NAMS onset: HadCM2 mean for the southwestern U.S. (heavy solid curve); observed mean for the southwestern U.S. (Higgins et al. 1997) (light solid curve); HadCM2 standard deviation for the southwestern U.S. (light dashed curve); HadCM2 mean for the central U.S. (heavy dashed curve) (from Arritt et al. 2000).

7. MODEL TRANSFERABILITY: COORDINATED ENHANCED OBSERVATIONS AND THE GLOBAL CONNECTION:

7.1. Background

Water and energy fluxes between the land surface and the atmosphere result from a very heterogeneous and complex system. The modeling of this coupled system relies at present on parameterization and empirical relationships. The performance of these coupled models in terms of systematic and random errors can vary over large ranges. The development of these coupled models has largely focused on regions having sufficient data to successfully use the approach of parameterization and empirical relationships. The development of a global land area-hydrology model needs an approach that can be successful in data sparse regions as well as demonstrate skill across a spectrum of continental climatic zones and forecast time scales. The latter approach is often referred to as "Model Transferability".

Progress in the representation of land-atmosphere interactions over the last two decades has been sufficient to motivate several operational modeling centers (for example, the National Centers for Environmental Prediction (NCEP), the European Centre for Medium Range Weather Forecasting (ECMWF), and the Japanese Meteorological Center (JMC)) to implement and benefit from modern-era, multi-layer soil-vegetation- atmosphere transfer schemes. Planetary, continental, and regional atmospheric circulation patterns in such assimilation systems are constrained near truth by the assimilation of atmospheric observations. Nonetheless, the implementation of improved representation of hydrologic-atmospheric interactions has undoubtedly improved the quality of the precipitation and low-level temperature analysis products provided by data assimilation systems.

For the past five years there has been an extensive effort to acquire the model output from several operational/experimental centers from a range of operational models of varying resolution, physics and data assimilation systems. GCIP is concentrating on three regional mesoscale models (IGPO, 1995):

- Eta model operated by NOAA/NCEP,
- MAPS model operated by NOAA/FSL, and
- GEM model operated by MSC/CMC.

The participation by the operational centers in providing regional model output for GCIP leads to a mutually beneficial relationship. The principal benefit to GCIP is to provide a measure of the inter-model variability of the outputs from the different regional models that can also be related to the global model output from the operational centers. GCIP provides benefit to the operational centers by enabling them to make use of the enhanced data sets and research results to calibrate and validate the model data assimilation and forecast systems.

7.2. A Coordinated Enhanced Observing Period (CEOP) and Global Land Surface Modeling (GLSM)

During the 2001 to 2007 time frame, GEWEX, through its Hydrometeorology Panel, is implementing a strategy to globalize its land surface understanding and the models developed through GCIP and other GEWEX Continental-scale Experiments (CSEs) (BALTEX, MAGS, GAME and LBA). To effectively provide GCMs with comprehensive land surface schemes, functional over the earth's entire land mass, the sensitivity of land surface physics and parameterizations to model scale and to processes not occurring in the USA will need to be understood. GAPP will provide leadership within the GEWEX Hydrometeorology Panel and CLIVAR in addressing this issue. A special GEWEX Coordinated Enhanced Observing Period (CEOP) will be a central initiative in acquiring data sets and initiating the modeling studies needed to realize the objectives of model transferability. CEOP will increase the value of GAPP (and GEWEX) to the academic and operational communities in the USA because it will increase the opportunities for global and regional climate modelers to have access to detailed information on land surface conditions for representative climate regions around the world.

The atmospheric circulation and the resultant climate pattern results from atmospheric heat sources and sinks. Heat sources and sinks over land and their influences tend to be seasonal in nature. Anomalies in the sink and sources effects are often propagated through teleconnections patterns. CEOP is designed to obtain data sets that can be used to determine the role of large scale forcing in these larger scale circulation patterns and the degree to which these teleconnections may reflect the transmission of anomalies from one area to another.

Studies of the low-level jet will build on existing infrastructure in the region and possible enhancements will also serve as a contribution to CEOP. A key GAPP contribution will be DOE's CART/ARM site where GCIP has installed a soil moisture network. Another nearby on-going data source is the Walnut Creek watershed that has been instrumented by the Cooperative Atmosphere-Surface Exchange Study (CASES). It is anticipated that AMERIFLUX sites and towers from GAPP studies in the Southwest would also contribute to this initiative.

The initial emphasis will be on data rich basins and regions, and then on data-sparse regions. During the later stages of GAPP, transferability studies will be carried out for land areas in different climate regimes around the globe. Transferability studies involving different geographical areas and models developed in different countries and institutions pose a number of challenges. Agreement on formats, definition of terms (e.g. soil moisture), process representation, degree of "tuning" or parameterization are just a few of the issues that must be addressed. The resultant generalized land surface models and parameterizations will be incorporated into global climate models to enable them to contribute to the more accurate prediction of atmospheric and hydrologic fields and phenomena on all time scales. These later studies will be a critical element for the global seasonal prediction efforts planned for the 2006-2007 time frame.

GAPP will be an integral part of the United States Water Cycle Initiative. By using these data sets obtained from NASA's Global Water and Energy Cycle (GWEC) initiative in GAPP's contribution to CEOP the utility of mesoscale models, land surface models and distributed hydrologic models in different regions including data sparse areas will be tested using parameters derived from satellite data and conventional data. As part of its prediction system development strategy, GAPP will incorporate these new land surface schemes initially into high-resolution regional climate models embedded in a global model and, when available, into high resolution global climate models in order to improve their ability to simulate the variability of climate and to utilize the full suite of remote sensing data that will be available from newer generation satellites.

7.3 Scientific Background and Questions

The scientific and technical objectives are encompassed within two overall CEOP objectives with each having several specific scientific objectives. The first overall objective is to demonstrate added skill in predictions up to seasonal for water resource applications using improved land-hydrology models.

Within this overall objective GAPP will contribute to four specific sub-objectives:

1. Evaluate the performance of regional coupled and uncoupled land-hydrology models across a spectrum of continental climatic zones and forecast time scales,
2. Achieve a better understanding of the land area and atmosphere interactions for improving the coupled hydrologic/atmospheric models,
3. Demonstrate the utility of the new generation experimental satellites in land area and hydrological research to improve NWP and climate predictions, and
4. Prepare global land data assimilation products for at least one complete annual cycle during the two-year data collection period.

The second overall objective is to conduct coordinated regional experiments in the significant heat source and sink regions, such as the Asian-Australian monsoon, the American monsoon and the African monsoon, that drive and modify the climate system and anomalies. Within this sub-objective GAPP will contributre to the study of the American monsoon by:

- Improving the simulation of the North American monsoon and to a lesser extent the South American monsoon,
- Improving the model representation of land surface processes, including snow and soil freezing processes, and

- Evaluating the model-simulated and predicted snow cover/soil moisture/monsoon relationships in terms of their ability to actually represent the observations.

Land areas are a fundamental aspect of the climate system but the contributions of their widely-varying surface, subsurface, and atmospheric boundary layer features and processes have not yet been adequately accounted for within predictive approaches.

Within the context of the CEOP objectives given above, key specific scientific issues for GAPP include:

- How do land areas respond to the large-scale climate system?
- How do atmosphere-land surface interactions operate and feed back onto the regional and larger scale climate system?
- How do these interactions operate over cycles from the diurnal to the annual cycles and what are their most critical periods and time scales governing their feedbacks to the overall circulation?

The focus of the specific scientific issues will vary over different parts of the Earth. GAPP along with other mid-latitude regions such as BALTEX (Baltic Sea) and many areas of GAME (Asia), will choose natural focal points that are more concerned with extra-tropical phenomena including summer features linked with heavy precipitation and the abilities of the region to recycle moisture. These specific scientific issues are all linked to the fundamental CEOP question, "How does land-area water and energy cycles operate and how are they linked with predictability?"

Collectively, CEOP therefore represents a unique opportunity to bring the GEWEX CSEs together to improve the scientific basis needed to achieve the overall GHP prediction goal.

7.4. Modeling Activities

GAPP and broader GHP coupled modeling activities to date have demonstrated success, and the results have been implemented in the Numerical Weather Prediction

(NWP) models run operationally at the NWP Centers. These modeling results have been developed and evaluated largely from the data obtained within the CSE region. The extension of these regional models to other geographic and climate regions is an important prerequisite to transferring the land/hydrology components to global NWP and climate models.

7.4.1. CEOP Model Evaluation Studies

A critical aspect of hydrometeorological modeling success is to develop quantitative relationships between small and large scales. Adapting scientific results achieved at one scale to applications on another scale is also a critical aspect of hydrometeorological modeling. The overall approach for the model evaluation studies is depicted schematically in Figure 7-1.

The overall objective of this CEOP and GAPP activity is to evaluate the performance of coupled hydrologic/atmospheric models in different geographical and climate regions as well as the performance of coupled model components over the same region at different temporal and spatial scales. For this reason, the GHP model transferability studies to which GAPP will contribute include at least three coupled hydrometeorological model case studies with the following characteristics:

1) A relatively simple geographic region without major topographic complexities such as the Mississippi River basin that has sufficient observations for data assimilation as well as model evaluation studies,
2) A complex geographic region, such as the Baltic sea and surrounding land areas now being studied by the BALTEX CSE, and
3) A neutral geographic region, that has not been studied by any of the CEOP participants, such as the region of the Niger River basin of West Africa, CATCH, that has been approved as a GHP affiliate project. GAPP also intends to promote studies in the Sakatchewan and Rio de la Plata River Basins.

For purposes of conducting model transferability studies, four types of studies are being considered:

Type 1 - “Home-based” global model using CEOP Validation Data (mainly Reference Site Data),

Type 2 - “Home-based” global model: Embedded Regional Model Comparative Evaluation with “Home-based” Regional Model Output during CEOP plus GAPP and CEOP Validation Data,

Type 3 - Model transferability Intercomparison using a Neutral Global Model” (e.g. ECMWF or NCEP/NCAR reanalyses), and

Type 4 - Regional Model embedded in different global models to evaluate the effects of initial and boundary conditions from the different global models.

7.4.2. Coupled Model Transferability Studies

The CSEs are being conducted in continental areas that are physiographically, ecologically, and climatologically diverse. Regional hydrometeorological processes and regimes are affected by many local variables, including topographic gradient and aspect, drainage pattern and density, soil texture, permeability, groundwater and water storage capacity, soil moisture, land-cover type and density and irrigation. From the perspective of coupled atmospheric/hydrologic modeling, these CSE regions provide excellent opportunities to conduct transferability experiments with regional coupled hydrologic/atmospheric models. A sampling of unique features that exist in different regions include the following:

- Highly continental climates as demonstrated by the pronounced annual cycles, limited atmospheric moisture sources, and overall semi-arid conditions.
- Pronounced local and remote effects of topography on the hydroclimate of the experimental basins.
- Pronounced diurnal cycle of precipitation during the warm season with nocturnal maximum.
- Significant snow measurement and modeling problems, including snowmelt timing with regard to runoff and other water budget components.
- Large-scale spatial variations and significant smaller scale heterogeneity in land-surface conditions (terrain, soil moisture, vegetation cover, etc.).

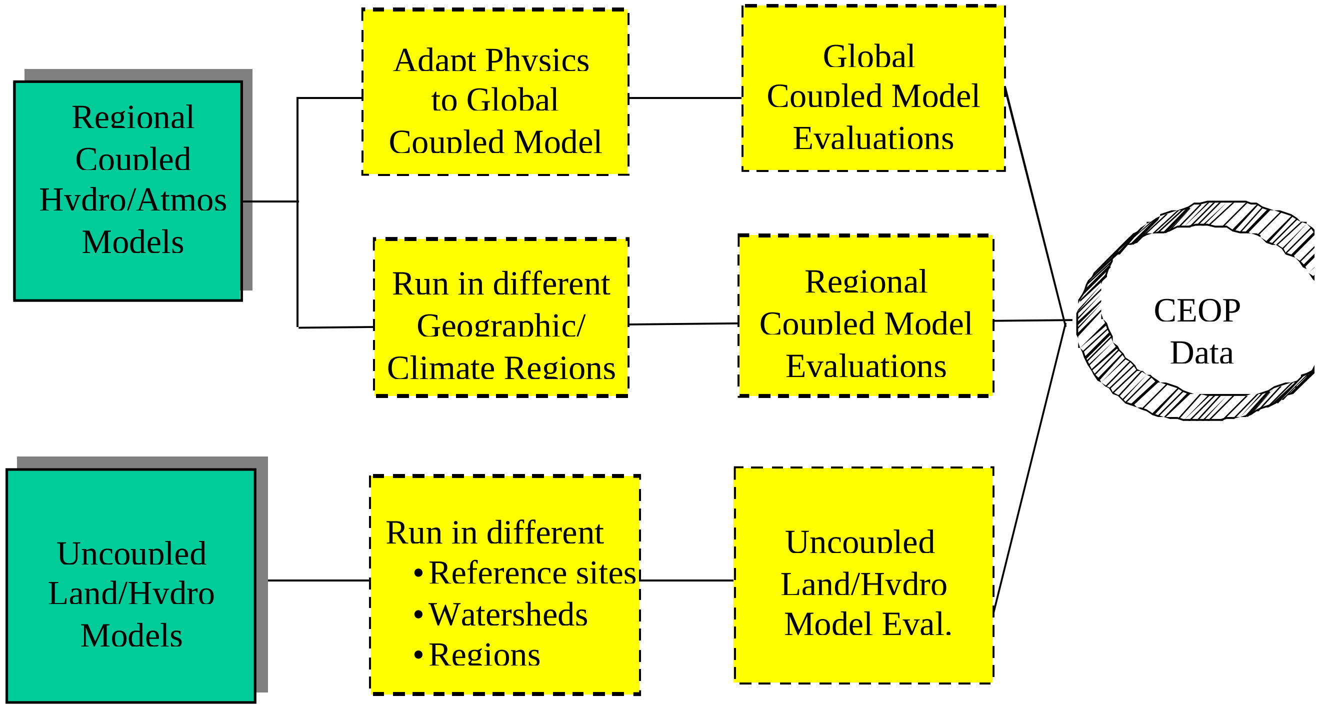

Figure 7-2 CEOP Model Evaluation Studies

GAPP will contribute to GHP coupled modeling activities of identifying and understanding the coupled processes that influence predictability at temporal scales relevant to water resource applications, and to develop coupled models, which can be validated at these scales using data from the different geographical regions. The regional effects include terrain characteristics, soil moisture, snow, land-use, vegetation cover, and other factors relating to the energy balances at the surface, and particularly, the partitioning of sensible and latent heat fluxes at the surface as indicated by the Bowen ratio.

Different regions of the Earth's landmass present complex scientific issues, and a number of opportunities and challenges for coupled modeling research. For example, great strides have been made in developing and validating land-surface and hydrology models by the CSEs within their own region, and implementing land-surface/hydrology models in regional weather forecast models. It is, therefore, necessary to assess these land-surface/hydrology models, both in off-line and coupled modes, for other areas in order to address the issue of transferability of models among different hydroclimate regions, and to provide insights regarding needed improvements of land-surface and coupled models. This point is also true for other coupled model sub-components such as cloud, precipitation and the parameterization of radiative processes.

In order to achieve the objective stated at the beginning of this chapter, four research priorities are identified:

1. Evaluate and improve the representations of the effects of seasonally varying land-use, soil moisture, vegetation cover, and other soil characteristics and their spatial heterogeneity in regional coupled models.
2. Determine and model the multiscale responses of complex terrain on the regional hydroclimate at diurnal and seasonal time scales.
3. Examine the models' surface energy budgets to evaluate the performance of the parameterizations used to describe the physical processes.
4. Characterize and model the temporal and spatial distribution of different land surface conditions, such as snow cover, including its accumulation/melt and the impact of frozen ground and on atmosphere/hydrology interactions.

Within the context of CEOP, GAPP will undertake research activities directed at:

(I) Developing and validating coupled model subcomponents and macro-scale hydrologic models in both stand-alone and coupled modes. An emphasis will be placed on improving the precipitation and runoff processes related to phenomena such as spring snow accumulation, snowmelt and infiltration. Evaluations of the performance of these model components would constitute a relatively stringent test of the transferability and the applicability to regions such as an overall semi-arid environment with a large annual cycle, complex terrain, and large spatial and year-to-year variability.

(ii) using coupled model experiments at large-scales to understand the effects of terrain and the seasonal evolution of various land-surface forcing components (e.g., snow cover, ground water, irrigation, soil moisture, land-use, vegetation cover, etc.) on mean seasonal and diurnal cycles. One important research issue involves the interactions between the land-surface process (e.g., soil moisture, land-use, and their heterogeneous spatial distribution) and the formation and evolution of mesoscale convective complexes. In addition, the effects of coupled model structure and factors such as resolution on the simulation of seasonal and diurnal land-surface/atmosphere interactions in complex terrain regions will be documented.

(iii) Assessing and comparing the regional performance of operational mesoscale models in terms of surface energy budgets. Despite the important advances achieved in coupled modeling, deficiencies in energy budgets have been detected in diagnostic studies and through careful comparisons with observations. Timely evaluations can contribute to closing regional energy budgets and improving the quality of CEOP data archives.

(iv) Conducting model and diagnostic case studies at small and intermediate scales for several anomalous occurrences. This study should include analysis of the physical processes and extreme events using extensive data collected at the GAPP CEOP Reference Site.

(v) Developing and evaluating techniques for assimilating new satellite remote-sensing data products and other more conventional data. By participating in CEOP, GAPP will need access to new satellite products including the Landsat-7 detailed land-cover, vegetation mapping and derived products, and the suite of surface and atmospheric observations provided by the Earth Observing System (EOS), ADEOS II and other orbiting platforms.

(vi) Investigating orographic-precipitation processes during the warm season, such as orographic uplift of an airmass over the U.S. Great Plains during large-scale easterly flow conditions. While research related to improving the current precipitation process in operational models must continue, exploratory research is also required to evaluate the value of successively nested coupled models (with resolution down to 2-3 km) as a possible downscaling method for applying seasonal-to-interannual forecasts to water resource issues.

(vii) Developing a better understanding of cold season precipitation and hydrology processes including snow and frozen-ground physics under the influence of complex terrain. The central issue is to improve the coupled model precipitation forecast skill so that it gives an accurate measure of the temporal and spatial distribution of snowfall.

7.5 Americas' Model Transferability Experiments

To date, results from the GCIP, LBA and MAGS modeling activities have demonstrated significant improvements that have been implemented in the NWP models run operationally at the NWP Centres. The extension of these regional models to other geographic regions on the North and South American continents provides some excellent opportunities to conduct model transferability studies. Some specific cooperative activities are planned during the CEOP period within the context of Americas' Model Transferability Experiments (AMTEX). The overall objective of AMTEX is to complete to the extent possible, an evaluation of the performance of coupled land/atmospheric models over the different geographic and climatic regimes of the Americas' continental regions.

7.5.1 Model Transferability Studies over the Canadian Prairies

The model output from the Eta, GEM and MAPS models are being archived during the GCIP Enhanced Observing Period. These models are expected to be operational during the CEOP data collection phase and could provide model output data for model transferability studies over the Canadian Prairies. It should be noted that the Canadian Prairie region is bounded on the North by MAGS and on the South by GCIP and includes the BOREAS study sites.

The plans for MAGS II include a model transferability experiment entitled SAGE (Saskatchewan and surrounding Area GEWEX Experiment). The objective of SAGE is to carry out a demonstration test of the degree to which our understanding and model capability that has been developed in MAGS is sufficient to also account for the

Saskatchewan River basin's climate system. The assessment of water and energy fluxes and reservoirs that occur over this region is a key scientific issue for SAGE.

The implementation strategy for SAGE is an 'experiment' covering a period of at least one annual cycle. This period 'limits' the effort to a doable task. The specific period chosen for the test is the 2001-03 period of the CEOP data collection phase. An unprecedented amount of information on water and energy fluxes and reservoirs, as obtained from several new satellite systems, will characterize this period. This initiative will also ensure that MAGS fulfills its obligation to demonstrate that its techniques and models are transferable to at least one other region. It is anticipated that GAPP will also participate in SAGE as part of its model transferability studies.

Subject to funding availability, the SAGE experiment planned by MAGS II could provide an excellent opportunity to continue the cooperative model evaluation studies that proved so successful during the GCIP Enhanced Observing Period. The Canadian Prairies, as a region between the GCIP and MAGS study areas, is important for both GAPP and MAGS II to assess their ability to 'transfer' modeling capabilities from one region to another in spite of major differences in large scale and local forcing.

7.5.2 Model transferability studies over the La Plata River basin

The La Plata River basin in southeastern South America covers an area of approximately $3.6 * 10^{6}$ km^{2}, which is slightly larger than the Mississippi River basin ($3.2 * 10^{6}$ km^{2}), and provides water resources for one of the most densely populated regions of South America. Furthermore, several hydroelectric power plants regulate the river flow and, in turn, can affect the navigability of these natural waterways. Lastly, harvests and livestock that are dependent on water are also essential for the region. All these elements are greatly affected by precipitation variability and more generally by changes in the hydrological cycle (Berbery and Collini , 2000)

The La Plata River basin in South America is an important region within the CLIVAR/VAMOS subprogramme for its studies of the South American Monsoon system with specific emphasis on the South American Low-Level Jet. Recently, there has been an effort to develop a Continental Scale Experiment to study the hydroclimatology of the La Plata River basin; such initiative would provide another link between the GEWEX interests on hydrological issues with CLIVAR/VAMOS concerns in monsoonal circulations. In addition, because the La Plata and Mississippi River basins have scientifically interesting similarities and differences, it affords an excellent opportunity to conduct transferability studies, such as the transfer of the Eta Regional Model developed largely in the Mississippi River basin to operate in the La Plata River basin which could be a precursor to a more complete continental scale experiment in this region after CEOP.

GAPP would also benefit by using its models in a different region to test and evaluate the physical parameterizations currently in use, and, thus, develop more robust representations of regional climatological features.

The transferability studies will encourage two types of exchanges:

- Interactions between Forecasting Centers (e.g., NCEP and CPTEC, or other regional centers) that provide crucial data sets (e.g., regional analyses and forecasts) to the scientific community.

- Interactions between Research Centers (e.g., Universities) that will have the responsibility of doing basic research to: (a) improve models' parameterizations in their respective regions of interest; (b) perform diagnostic studies of the water and energy budgets; and (c) contribute to develop hydrometeorological applications.

However, both activities need to be linked to allow feedbacks between operations and basic research. GCIP has set a clear example on how operational forecast centers and research institutes should interact, and the benefits have been widely recognized; the same approach should be taken during GAPP and CEOP. In particular. effort should be devoted to the development of local data sets that can be shared by the community for evaluation of models and tuning of parameterizations. Also the infrastructure being developed in GEWEX Land Atmosphere Simulation System (GLASS) should be part of these model transferabiltiy studies.

8. TOWARD AN INTEGRATED SEASONAL PREDICTION SYSTEM:

8.1. Rationale

An integrated seasonal prediction system that can further advance both cool season and warm season prediction skill at the smaller regional scales needed for meaningful water resource management will require a) coupled modeling of the entire earth system (land, ocean, atmosphere), b) companion data assimilation systems for land, ocean, atmosphere, and c) spatial downscaling via 1) imbedded land-atmosphere regional climate models and 2) distributed macroscale land/hydrology models.

The pathfinder research already accomplished by the GEWEX program, and its sub-programs such as GCIP, ISLSCP, GSWP, and PILPS in the area of land modeling, land atmosphere coupling, land data assimilation, and regional climate modeling, together with the companion ocean modeling initiatives and pathfinder successes arising from the TOGA and CLIVAR programs, have provided all the pilot components to construct and demonstrate an integrated, end-to-end, multi-scale, land-ocean-atmosphere seasonal prediction system, such as that depicted in the schematic of Figure 8.1

8.2. Objective

One of the two objectives of GAPP is to develop and demonstrate a reliable monthly to seasonal prediction system for precipitation and land surface hydrologic variables and to provide and demonstrate the contribution of the land modeling component to this seasonal prediction system. This task will be accomplished through improved representation of the land surface and related hydrometeorological and boundary layer processes. Within the limits of predictability in the climate system, GAPP will determine how the improved representation of these processes lead to an improved prediction capability (especially warm season) and improved water resource management utility. It is anticipated that water resource applications will require one or more of the downscaling components represented in the schematic of Fig. 8.1. Accordingly GAPP will seek to demonstrate the relative value added by:

1) The improved physical modeling and initialization of land memory and feedback processes at a given modeling scale in Fig. 8.1, and
2) The orderly successive downscaling of the multi-scale modeling components of Fig. 8.1

8.3. Background

It is now widely acknowledged that the intrinsic chaotic nonlinear nature of atmospheric circulation and weather systems imposes a limit of about two weeks on deterministic prediction of atmospheric weather (Lorenz, 1982). However, in the neighborhood of this limit (medium range of 5-15 days) and well beyond this limit (seasonal and annual range of 1-12 months), pathfinder efforts at extended-range dynamic model prediction have shown that the combination of ensemble prediction methods, time and space averaging, and coupling of ocean-atmosphere-land models (Shukla, 1993) can yield extended-range predictability of time-mean regional anomalies of temperature and precipitation. This extended range predictability of departures from normals arises from the quasi-persistent low frequency atmospheric variability that is forced by the lower boundary anomalies in sea-surface temperature (SST), soil moisture, snowpack, and vegetation.

To date, the analysis and prediction of ocean SST anomalies in coupled ocean-atmosphere GCMs has been the principal route to successful seasonal prediction (Ji et al., 1994), and this success primarily in ENSO-related anomalies in the Northern Hemisphere winter season general circulation. However, a growing body of research literature, such as that sponsored by GCIP and GHP, is demonstrating emerging success at warm season predictability arising from the advancement of land-surface influences through improved a) land-surface models and land-atmosphere coupling (Koster and Suarez, 1999; Fennessy and Shukla, 1999) b) land data assimilation (Dirmeyer and Brubaker, 1999; Douville and Chauvin, 2000), and c) embedded land-atmosphere regional coupled climate models (Fennessey and Shukla, 1999; Giorgi and Mearns, 1999; Pielke, 199X; Leung et al., 199X)

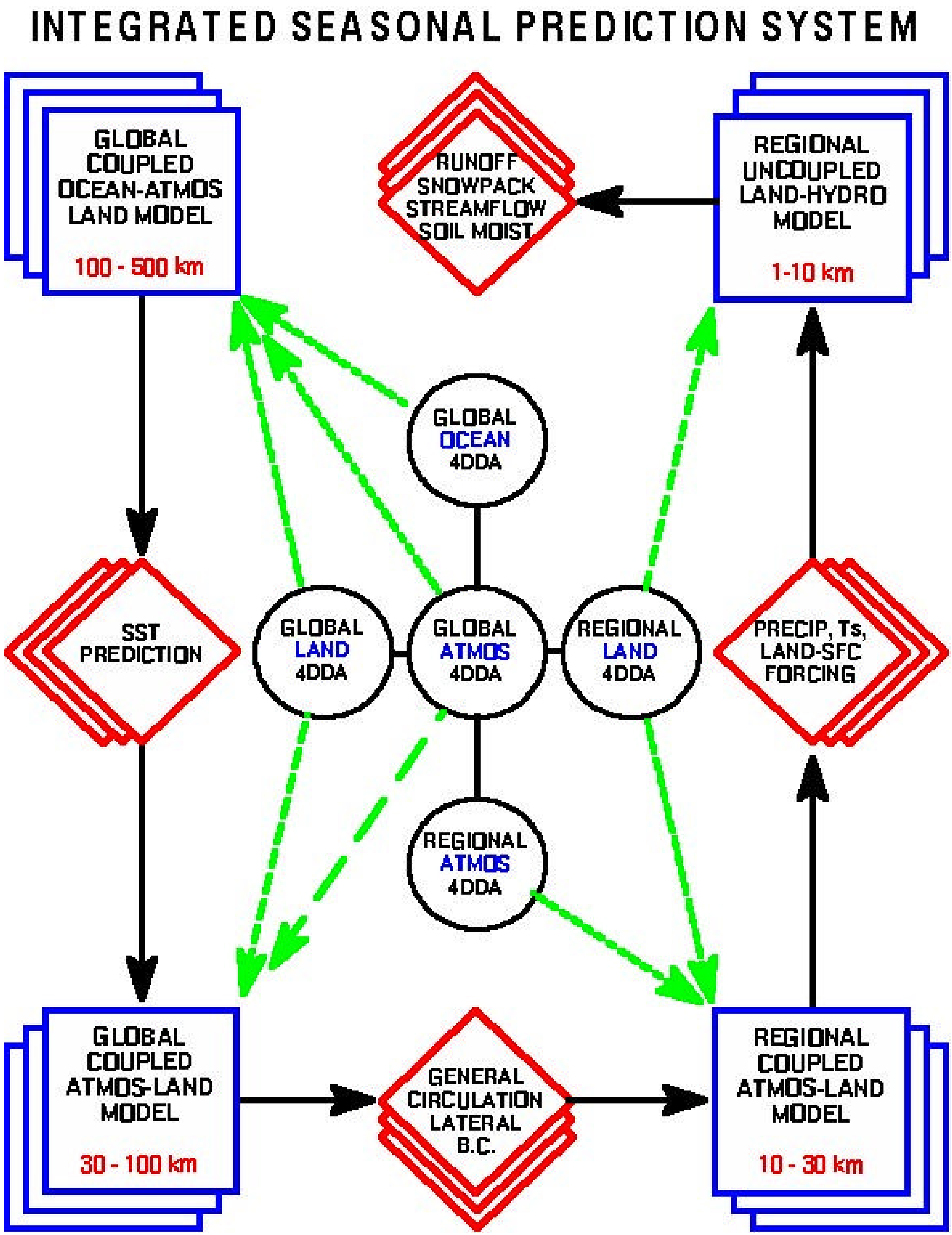

Figure 8.1. Integrated Multi-Scale Seasonal Prediction System

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A review of this literature strongly suggests that the further advancement of seasonal predictability, especially in the warm season will likely require:

1) Simultaneous coupled treatment of the full earth system including land, ocean, and atmosphere: -- adding equal emphasis to land-atmosphere coupling, as highlighted in the GEWEX program, to complement the ocean-atmosphere coupling thrusts of the TOGA-COARE and CLIVAR programs,
2). Companion land, ocean, and atmosphere data assimilation systems: -- land data assimilation systems and research, such as those now arising in GCIP and sister GEWEX programs (Mitchell et al., 2000) , to complement traditional atmospheric data assimilation systems, and maturing ocean data assimilation systems (Beringer et al., 199x) and ocean data assimilation research, such as the ODAE,
3) Downscaling using nested multi-scale regional land-atmosphere climate models and uncoupled macro-scale distributed hydrological models, and
4) Ensemble prediction sets that employ not only an ensemble of initial conditions, but also a range of physical parameterization packages for land, precipitation microphysics, convective parameterization, and radiation/clouds.

8.4 Approach

The components of the seasonal prediction system in Fig. 8.1 will be provided (and upgraded) by:

1) Principal GAPP initiatives to determine the predicatbility associated with land surface memory processes, orographic effects and monsoonal cicrculations, and
2) Existing components and infrastructure that have already emerged from GCIP, other GEWEX Continental Scale Experiments and initiatives, TOGA, and CLIVAR, including those components currently in use at operational and research seasonal prediction centers (NCEP, OH, COLA, IRI), government labs (LLNL, NCAR), and universities.

Pilot versions of all components of Fig. 8.1 already exist, including those already developed in GCIP, but during the GAPP era they will be substantially upgraded and assembled into a connected unified system. This integrated end-to-end seasonal prediction system may emerge in different systems at several facilities. These alternate systems will allow a dual development pathway that will give different emphasis to:

1) Retrospective runs that will be carried out, with a prime emphasis on sensitivity studies focusing on predictability science questions seeking to establish the relative sources of predictability skill (e.g. SST versus soil moisture, embedded regional models versus more global ensembles), and
2) Realtime prediction runs that will be executed, providing experimental seasonal forecasts for use in pilot water resource management studies.

8.4.1. Land Surface Modeling

One goal of GAPP is to promote and demonstrate the use of a single, unified land surface model (LSM) in all components of Figure 8.1, hence a land-surface model or models that are transferable to any climate regime globally and is able to perform robustly at multiple scales in models ranging from 100 km to 5 km resolution. This goal may be accomplished by such approaches as the tiling or aggregation methods to represent sub-grid variability. Given that various renditions of Figure 8.1 may emerge at several facilities, this fact will allow several different LSMs to demonstrate their multi-scale utility.

GAPP will carry forward the legacy of GCIP, PILPS, and GSWP and continue to sponsor the intercomparison of leading land surface models, with a focus on spearheading initiatives that yield increased convergence in the behavior of leading LSMs under conditions of identical surface forcing and land-surface characteristics. As Figure 8.1 suggests, these land surface models should be tested and applied in three modes, namley:

1. as uncoupled quasi-distributed macroscale hydrology models,
2. as the land component in global and regional climate and NWP models, and
3. as the land component in global and regional land data assimilation systems.

8.4.2 Land Data Assimilation Systems

GAPP will spearhead the development and demonstration of both global and regional Land Data Assimilation Systems (LDAS) in both uncoupled and coupled modes. An LDAS is the crucial component that will provide the initial conditions of soil moisture, soil temperature, and snowpack for the integrated seasonal prediction system. The central element of each LDAS will be the land surface model (LSM) that will derive the physical background states by assimilating land-surface observations and large-scale atmospheric forcing will be assimilated.

A key thrust of some LDAS initiatives will be to demonstrate whether the imminent state-of-the-art assimilation of gage-, radar-, and satellite-derived precipitation estimates in coupled systems is sufficient to overcome the typically severe precipitation biases that characterize existing present-day coupled 4DDA systems. Until a coupled assimilation system with realistic precipitation patterns is achieved, the LDAS for the integrated seasonal prediction system will remain uncoupled, directly using the gage, radar, and satellite precipitation estimates in direct surface forcing.

A second key thrust of GAPP LDAS initiatives will be the development of algorithms for the assimilation satellite-derived land-state information (soil moisture, vegetation, snowpack, skin temperature) (Houser et al., 1998; Reichle, 2000). This will include the development of so-called adjoint models and tangent-linear models needed by modern-era variational assimilation methods. In this context, new forward radiative transfer models must be developed to transform LDAS land states and surface characteristics into the satellite radiance channels (e.g. microwave) sensed by the growing number of satellite instruments in the EOS era. Other potential applications of satellite data are outlined in Chapter 10.

8.4.3. Imbedded Regional Climate Models

Recent studies are establishing that high resolution regional climate models driven by time-dependent atmospheric lateral boundary conditions (LBC) from a coupled GCM can be used to successfully downscale climate simulations generated from relatively coarse resolution global models (Semazzi, 1999; Giorgi and Mearns, 1999; Fennessy and Shukla, 1999; Mo et al., 1999; Hong and Leetmaa, 1998; Kim et al., 2000; Leung et al., 199X). For example, Fennessy and Shukla (1999) provide striking examples of warm season precipitation predictability improvement via an imbedded regional model compared to the parent global model and other global models.

Imbedded regional climate models are successful because the higher resolution imbedded models can provide better resolution for 1) the influence of orography, especially the role of regional elevated heat sources as important forcing mechanisms for monsoon circulations, 2) the diurnal cycle of moisture advection, especially the summer season low-level nocturnal jets prominent in south central U.S. and central South America (Berbery et al., 1996; Berbery et al., 2000), 3) summer season nocturnal precipitation maxima associated with the nocturnal jets, 4) SST gradients in nearby coastal ocean areas, and 5) mesoscale convective complexes, which play a dominant role in summer season precipitation anomalies.

The full potential of this approach still requires substantial research and development to address the issues and problems of 1) model spin-up, 2) incompatibility between regional and global model physics, 3) trade-offs of model domain size and resolution, 4) discontinuities introduced by the lateral boundary conditions, 5) one-way versus two-way nesting, and 6) solution splitting between the imbedded regional model and parent global model.

8.4.4. Coupled Ocean-Atmosphere-Land GCMs

The TOGA research program, and the follow-on CLIVAR program, have provided a progression of initial successes and follow-on improvements to coupled ocean-atmosphere GCMs, ocean state initialization and data assimilation (Cane et al., 1986; Zebiak and Cane, 1987; Ji et al., 1994; Chen et al., 1995; Behringer et al., 1998; Ji et al., 1998). GAPP will utilize the coupled ocean-atmosphere GCMs and ocean data assimilation systems emerging from these programs. The GAPP focus on the GCM scale will be to provide the land surface model component and the global land data assimilation system (GDAS) for the coupled land-ocean-atmosphere GCMs.

8.4.5. Generation of Ensemble Predictions

All the forecast components of Figure 8.1 will utilize ensemble predictions. Following the tradition of medium range predictions (1-2 weeks), ensemble forecasts invariably are produced from a group of modestly varying initial conditions for the atmospheric state, created by adding perturbations to a mainline operational atmospheric initial analysis (Toth and Kalnay, 1993; Molteni et al., 1996). This philosophy of generating ensemble forecasts merely from a range of initial atmospheric states is rooted in the medium-range perspective, wherein the implicit assumption is that the forecast model is "perfect" (i.e. no model uncertainties) and the resulting spread of forecast evolution results from the internal nonlinear dynamic response to only initial condition uncertainties. This assumption of perfect model clearly breaks down at seasonal and longer time scales. Even at the medium range, recent results (Harrison et al., 1999; Krishnamurti et al., 1999) indicate that model uncertainties have substantial impact on ensemble forecast spread, as evidenced by superior capture of forecast spread and realizations by using a) multiple models, b) multiple physical parameterizations in a given model (convection, radiation, gravity wave drag, horizontal diffusion, land-surface, etc), and c) stochastic perturbations to a given model's diabatic heating tendencies (Buizza et al., 1999). At seasonal forecast time scales, such approaches to model uncertainty will have to be utilized in addition to lower boundary condition uncertainty (i.e. extending initial state uncertainty to the land states of soil moisture, snowpack, etc, and ocean states of SST, salinity, etc).

8.4.6. Empirical Prediction Backdrops

As discussed by Kumar and Hoerling (2000), empirical approaches to seasonal prediction provide a fundamental backdrop to the dynamical model approaches of Figure 8.1. Empirical methods should be further explored, extended, and utilized, as applied forecast tools and as a baseline to compare to GCM-based skill. They argue that the advantage of GCM-based seasonal predictions versus empirical methods depends solely on the extent of nonlinearity of the observed atmosphere to SST forcings. Yet there is strong observational evidence that, at least in the case of El Niño episodes, there is a quasi-linear relation between the strength of the SST anomaly and the strength of the atmospheric perturbation. This point raises the prospect of only marginally increased seasonal prediction skill from GCM methods versus empirical methods for the intermediate term.

Similar empirical backdrops are needed in the context of downscaling. Noteworthy success has been achieved using empirical methods to downscale GCM seasonal predictions to smaller scales, and such methods have been notably competitive in some studies with the more expensive and demanding downscaling approach of using imbedded regional models. Such empirical downscaling success is again most likely in cases where the downscaling response is fairly linear (e.g. straightforward orography signature in a winter season precipitation anomaly in the Pacific Northwest). However, empirical downscaling will likely show minimal success in warm season situations where nonlinear feedback processes play a more dominant role.

Finally, despite the extensions to ensemble prediction methods outlined in the previous section, present and future ensemble forecasts suites will invariably 1) underforecast the spread of observed realizations and 2) skew the observed frequency of the spectrum of precipitation amount categories. Here again, empirical methods are emerging and must be further extended and expanded to better correct these ensemble suite biases.

9. HYDROLOGY AND WATER RESOURCES:

9.1. Rationale

One of the two primary objectives of GAPP is "To interpret and facilitate the transfer of the results of improved seasonal predictions to users for the optimal management of water resources." To accomplish this objective, it is necessary to understand: (i) what kinds of forecast products are most useful to water resources agencies; (ii) how this information could be used in water management decisions; and (iii) how this information can best be produced, and transferred to water managers. Addressing these issues will, in turn, help focus related science needs (e.g., development of improved hydrologic prediction capability).

The linkage between the science (hydrology) and applications (water resources) activities within GAPP is particularly important. GAPP, like GEWEX, is a science program, that also has a set of applications objectives. In this case, the scientific requirements involve the better understanding of large scale hydrologic processes over the GAPP domain, how they influence hydrologic predictability, and, in turn, the development of hydrologic prediction tools. With respect to time scale, the focus is on relatively long lead times (e.g., climate time scales of months to years). The applications objective is to improve operation of water resource systems using GAPP science. In the following chapter, we identify the primary science questions to be addressed by the GAPP hydrology and water resources initiative.

To accomplish its dual responsibilities to science and applications in the hydrology and water resources area, GAPP will complement its scientific projects with some applications activities, designed to help understand what kind of information is needed by water agencies and how it might be used. In particular, GAPP will undertake projects in collaboration with water agencies to analyze their current operations and basis for decisions and how they might make use of improved forecast information.

These activities (elaborated in Section 9.3) will include an assessment, for cooperating water resources agencies, of how operational decisions can make better use of improved seasonal to inter-annual forecasts.

To understand how improved hydrologic forecast information can be produced, collaborative studies between the academic community and operational hydrologic forecast agencies, such as the National Weather Service, will be initiated. GAPP desires to implement, in a manner similar to its current arrangement with NCEP, parallel research and operational pathways with an operational hydrology agency. The research pathway will involve targetted hydrologic research conducted primarily by scientists in the academic and government research laboratory community. It is anticipated that the operational pathway would be conducted primarily within the U.S. National Weather Services' Hydrology Laboratory and its affiliated River Forecast Centers. The NWS operational pathway would deal primarily with development of improved long-range hydrologic prediction capability, through testing and implementation of GCIP and GAPP hydrologic modeling advances. This research would supplement the Advanced Hydrologic Prediction System (AHPS) initiative of NWS by introducing climate time scales to that service. A second set of parallel activities would be implemented in conjunction with selected water management systems and agencies. These activities would start with research and operational hydrologic prediction tools, and test, in parallel with an existing operational decision tools, the implications of improved hydrologic forecast products for system operation.

The parallel pathway approach is designed to make GAPP research accessible to water managers and to provide a mechanism for feedback to the related science community. The process of technology transfer to the water management community will involve the following steps:

1. Research and development leading to retrospective intercomparisons to demonstrate the potential improvement,
2. Operational software enhancements and tests to demonstrate system reliability,
3. Parallel operational testing to demonstrate the validity of the improvement,
4. Documentation and training, and

5. User acceptance.

In Section 9.2, the science questions that will drive the research pathway are outlined. In Section 9.3, a set of research and applications activities are outlined, that summarize briefly the mechanisms that will be used to effect the technology transfer needs outlined above.

9.2. Science Questions

The GAPP Hydrology and Water Resources activity will be guided by six science questions, which will serve to focus the activity on the intersection between the scientific contributions of GAPP (and more broadly, GEWEX) and the water management community. These science questions are elaborated below:

Science Question 1: What are the key factors governing hydrologic predictability, and in particular, the ability to predict streamflow, evapotranspiration, and soil moisture? To what extent can improved process understanding, and its incorporation into hydrologic models, result in more accurate hydrologic predictions?

As defined by the NAS Committee on Hydrological Sciences (COHS), "Predictability is the extent to which the future state of a system can be estimated based upon the (theoretical) availability of a comprehensive set of observations characterizing the system's initial condition." The predictability of land surface hydrologic processes is thought to be attributable primarily to two mechanisms. As described in Chapter 4 the first mechanism is persistence due to the storage of moisture, as groundwater, snow and/or ice, soil moisture, and (manmade or natural) surface impoundments. The second is recycling of moisture stored on or near the land surface and the influence of the recycling process on moisture fluxes to and from the atmosphere. Therefore, the ability to make hydrologically useful predictions requires understanding of the storage of water as well as the factors controlling moisture fluxes, their variability, and the dynamics of the coupled land-atmosphere system.

In the western U.S., the mechanisms controlling hydrologic predictability are substantially different than in the GCIP study area (Mississippi River basin). In particular, the precipitation regimes in the West are dominant in the winter, and the role of orography in controlling the spatial distribution of precipitation and runoff production is a key factor. Evaporative processes as they affect precipitation (both directly and indirectly) are arguably less important. Understanding the role of snow, its interaction with topography, and the factors controlling its ablation, are crucial. On the other hand, evapotranspiration does control soil moisture antecedent conditions, which in turn controls runoff production. Likewise, the direct role of vegetation is somewhat different in the West than in the GCIP region. Runoff source areas are largely forested with nonforested areas generally contributing in only a minor way to streamflow. Exceptions are monsoonal conditions in the Southwest and flash floods on relatively small watersheds. Quantifying the effects of forests and deforestation on the hydrologic cycle are important research issues for this area.

Science Question 2: What is the best strategy for implementing distributed and semi-distributed hydrology models over a range of spatial scales, and how can the performance be evaluated? What are the relevant spatial scales, and how transferable are parameters? How do we develop a pathway for model improvements?

A major contribution of GCIP has been the development of a new generation of land-atmosphere transfer schemes, which represent both the energy and water balances of the land surfaces, at resolutions down to about 1/8 degree, and domains up to continental. Implementation of these new land surface schemes into the NCEP family of coupled land-atmosphere models has greatly improved their ability to partition energy at the land surface, among other things. The ongoing Land Data Assimilation System (LDAS) project (URL) is using several of these models to create better initial conditions for numerical weather forecasts. LDAS, and other GCIP activities, have shown that land surface schemes that properly represent runoff production (as a subgrid process) can also be used to predict streamflow over large continental river basins and their major tributaries. Less progress has been made in adaptation of these models in the operational hydrology community.

Distributed and semi-distributed hydrologic models, which are generally pixel-based (i.e., represent a watershed as a collection of rectangular elements) are distinguished from more conventional hydrologic models through their explicit use of land surface characteristics, including topography, soils, and vegetation. However, like more conventional models, they inevitably require some calibration, especially for parameters that are related to soil characteristics, which cannot be represented directly due to the large spatial scales involved. Furthermore, there is a concern as to how the parameters of these models depend on model spatial scale. Among the strategies for model implementation are regionalizing parameters through use of a representative set of Intermediate Scale study Areas (ISAs – typically catchments with drainage areas 10^2 – 10^3 km^2) over the region, and direct transfer from nearby, calibrated catchments. More generally, the evolving field of macroscale hydrological modeling (MHMs) creates an opportunity for a well-defined pathway for incorporation of improved physical understanding into hydrologic prediction. Such a pathway has proved quite successful in numerical weather prediction and has resulted in a documented history of continuously improving skill scores. Such a history is largely lacking in surface hydrology.

A parallel implementation question is how better models and supporting data can make the process of model implementation and testing more efficient. At present, implementation of hydrologic models involves a fairly time-consuming process of calibration and verification and is largely site specific. The hope in using more physically based models is that the number of free parameters will be reduced, and hence calibration simplified. To date, no rigorous studies have been performed to determine whether, and to what extent, this procedure is possible, although anecdotal evidence suggests it to be the case.

Science Question 3: What is the role of hydrologic prediction in coupled land-atmosphere modeling? Is one-way (or two-way) coupling in land-atmosphere models a viable hydrological forecasting strategy?

With the evolution of coupled land-atmosphere models, particularly MHMs that predict runoff and streamflow, as well as surface energy fluxes, the distinction between land surface models and hydrologic simulation models has become blurred. MHMs arose from the need within coupled land-atmosphere models to partition net radiation into turbulent and ground heat fluxes. This partitioning is coupled, however, with the surface water budget (because evapotranspiration is a common term in the energy and water balances). Therefore, MHMs predict not only energy partitioning, but also streamflow. As noted earlier the advantages of MHMs over more conventional hydrologic simulation models include more direct incorporation of physical process understanding, that should reduce the need for parameter estimation (see Science Question 1) and make greater use of modern high resolution land cover data, including soils, topographic, and vegetation information. However, there remain open questions as to how MHMs are best implemented in so-called "off-line" mode – that is, with surface forcings prescribed. Whether and how parameters vary depends on whether an MHM is implemented in "water balance" mode (basically meaning that no iteration is performed on the effective skin temperature, or in effect assuming the skin temperature is equal to air temperature) or an "energy budget" mode where skin temperature values are iterated by closing the surface energy budget. The assessment of the best approach is still an open question. More generally, there is a question as to the role of MHM predictions implemented in fully coupled mode, and how, whether, and under what circumstances it is more consistent to use a fully coupled implementation.

Science Question 4: What are the causes of biases in hydrologic model forcings and outputs? What are their effects on the potential use of hydrological model output in hydrologic prediction, and in turn in water resources system operation? How can these biases best be removed?

All dynamic models (as compared to statistical models, which can be designed to be unbiased) contain some bias. This fact is certainly true of atmospheric models, especially when evaluated with respect to their ability to reproduce observed precipitation. Hydrological models, even when forced with error-free surface meteorology, are inherently biased, especially for low flow conditions. Methods are evolving for removal of model bias (especially in atmospheric model surface variables).

These methods are of two general types. The first requires a retrospective climatology for both the model and observations, usually for a period of at least a decade. The second, “on the fly” method uses a shorter period, with additional assumptions that allow the information needed to perform the unbiasing from multiple storm events over a shorter period. Similar approaches can, in concept, be applied to hydrological model output.

Although these methods can eliminate hydrological model input and output bias, an unanswered question remains as to how the bias (and its removal) affect the information content of both the atmospheric and hydrologic forecasts. Attention should be given to the role of biases in both meteorological forecasts (forcings to hydrologic forecast models) and in the hydrologic models themselves. Every hydrologic model includes at least some seasonal bias in the statistical properties (e.g., means and variances) of model outputs when the models are operated in a simulation mode using historical observations. Some method of correcting for these biases is essential for use of the forecasts in water resource applications. The required corrections usually are accomplished through post processing of model outputs. Experiments are needed to demonstrate that the climatology of these hydrologic forecasts agrees with the climatology of historical streamflow events. In addition, useful methods to measure the skill in these forecasts need to be developed and demonstrated so that water resource managers can have the appropriate level of confidence in the forecasts.

Science Question 5: How can improved modeling strategies, like land data assimilation and ensemble forecasting, best be implemented in a hydrologic prediction framework? Where is the greatest potential, in both the short-term and long-term, for improving hydrologic predictions and forecasts? What is the interaction between the need and potential for improved observations and modeling in terms of operational forecasting?

The development of a Land Data Assimilation System (LDAS) has been a major undertaking of GCIP, which is expected to continue and broaden in scope under GAPP. LDAS was motivated by the problem of providing proper initialization for the land surface state variables (primarily soil moisture and snow) in NCEP’s suite of operational forecast models. In most current weather forecast systems, errors in the NWP forcings accumulate in the surface and energy stores, leading to incorrect surface water and energy partitioning and related processes. The problem is especially acute for precipitation, as precipitation errors lead to errors in soil moisture, which in turn affect surface energy partitioning during subsequent forecast cycles. LDAS consists of uncoupled models forced with observations, which therefore are not affected by NWP forcing biases. The observations include a merged precipitation gage and radar product, satellite data (primarily for solar radiation), and, at present, some forecast model analysis fields. Land surface model parameters are derived from high-resolution vegetation and soil data. LDAS has both a real-time pathway, that operates in parallel with the operational Eta model at NCEP, and a retrospective pathway, through which quality-controlled retrospective data can be used for parameter estimation and other purposes.

In addition to its immediate goal of providing better initial conditions for numerical weather forecasts, LDAS has implications for water resources management, as it provides a hydrologic prediction capability for large river basins. At present, this capability has been demonstrated primarily within the GCIP Mississippi River basin, as well as the Columbia River basin. Among the major issues to be addressed by LDAS under GAPP are: 1) what are the most important external forcings, and how can they best be derived independently of model analysis, 2) what improvements in weather forecasts result from the use of LDAS in comparison with more conventional methods, and what are the space-time characteristics of these improvements, 3) how can remote sensing data be used more effectively in LDAS, and to what extent can remote sensing data either extend or replace surface observations, and 4) how can LDAS be expanded to have a true data assimilation capability, e.g., through assimilation of remote sensed soil moisture, surface temperature, snow, and/or other variables?

Ensemble climate forecasting is a second area, in which advances under GAPP have the potential to improve hydrologic forecasts, which in turn has implications for water management. Water resources system simulations models are designed to process ensembles of events to evaluate the implications of alternative operating decisions when the future reservoir inflows are not known exactly. In other words, models need ensemble forecasts of reservoir inflows. In addition, ensemble prediction methods allow uncertainty in future precipitation patterns throughout a river basin to be analyzed in a way that is statistically consistent for all forecast points in the basin. In this context, analysis of climatological space-time precipitation climatologies should be undertaken to support verification and testing of precipitation forecasts, including ensemble precipitation forecasts. In addition, hydrologically relevant verification methods are needed to assess precipitation forecasts. This process includes techniques to assure that the climatology of precipitation forecasts (including ensemble forecasts) matches climatology (i.e. the forecasts are statistically unbiased). Also, hydrologically relevant approaches are needed to measure the skill in these forecasts over a range of space and time scales.

Science Question 6: How can the scientific contributions of GCIP/GAPP, in areas such as coupled land-atmosphere modeling, land data assimilation, and ensemble forecasting, best be transferred to the operational hydrology and water resources community? What are the implications of science issues to be addressed by GAPP, like possible tradeoffs between observations and model complexity as they affect forecast skill, and between the ability to characterize forecast uncertainty and forecast space-time resolution, to the operational community?

As noted above, GCIP has made considerable progress in the development of models, and modeling strategies, that have had important implications for understanding of water and energy budgets over the central U.S. and for the predictive capability of land-atmosphere models used in the operational weather community. GCIP has placed less emphasis on transferring those scientific advances to the operational hydrology and water management communities. Slow progress in this area can perhaps be attributed to two factors. First, the operational community is objective, rather than hypothesis, driven. That is, better understanding of the science ("why") isn't necessarily of immediate interest unless it helps in some quantifiable way in achieving an objective (e.g., making a more accurate forecast). Second, the operational community has a large investment in modeling structures that aren't necessarily compatible with the new generation of land-atmosphere models, and there has been, understandably, a “show me” attitude. It is incumbent on GAPP to develop an effective technology transfer strategy that can show the benefits (or lack thereof) in adaptation of new technology. In Section 9.3, a strategy is outlined which addresses the general problem of interaction with the operational community, as well as specifics of how scientific advances can be incorporated into operations.

The hydrologic community can look to the weather forecasting community to understand how the lead-time between advances in science and research and their inclusion in operational systems can be reduced. One strategy that has been used successfully in weather forecasting involves parallel research and operational pathways, wherein improved process understanding is translated to better parameterizations and algorithms that are tested in parallel with operational models. If and when the research path improvements are shown to result in forecasting improvements, they are adopted in a new “cycle” of the operational model. This approach has resulted in an ability to “fast track” scientific advances, which hasn’t been the case in the operational hydrology community, probably because there is no apparent model upgrade pathway in operational hydrology, analogous to those that have been adopted for NCEP’s suite of coupled land-atmosphere models.

The potential for a strategy utilizing parallel operational and research pathways addresses only the hydrologic prediction aspects of the GAPP technology transfer problem, however. The second part of the problem has to do with transfer of scientific improvements, as represented by GCIP and GAPP models, to the water management community. This problem is somewhat more complicated conceptually than the hydrologic prediction problem, because the decision process is much more distributed. There is a question as to how involved a program like GAPP (or more generally GEWEX) should become in the water management decision process. GAPP will make its greatest impact by facilitating some “joint ventures” with water managers. This process may well involve demonstration projects or similar mechanisms. Such projects would have to deal not only with the modeling and prediction issues, but also with the use of improved predictions in a decision framework. This perspective is a somewhat different for a science-driven program like GAPP, and may well require interactions with the OGP Human Dimensions and Regional Assessment activities. In the following section, we suggest some possible implementation pathways.

9.3. Research and Applications Activities

The GAPP research program will be carried out through a set of activities, to be organized around individual GAPP supported research projects, related non-GAPP research projects, related operational activities of the NWS hydrology program, and other activities of NASA, NOAA and other agencies. These activities will be structured within parallel research and operational pathways, following the successful GCIP structure for coupled model development.

The overarching GAPP strategy for hydrologic prediction, and its incorporation into water resources decision making, follows the so-called “Shukla Staircase” outlined at the 1998 GCIP/ PACS Warm Season Preciiptation Workshop (Silver Spring, MD). A slight variation of the Shukla scheme is shown in Figure 9.1. It exploits global climate teleconnections; consequently its first step involves forecasting sea surface temperature anomalies globally. This element of the staircase relies on the considerable thermal inertia, hence persistence, in sea surface temperature anomalies. The SST forecasts are then used as boundary conditions for a global coupled land-atmosphere models, which subsequently, through nesting to the continental or finer scale, provides forcings for a macroscale hydrology model. As noted in Science question 3, there is an open research question regarding the need for two-way or one-way coupling with the land surface hydrology model at this step. In this case, the macroscale hydrology model then provides forecasts (in practice, multiple ensembles) to a water management model, which in turn is used in the management decision process. This entire procedure, sometimes termed end-to-end prediction, is conceptually straightforward, but has yet to be demonstrated in practice.

A major thrust of GAPP, and the hydrology/water resources activities in particular, is to develop and implement the approach, and to demonstrate its utility for “real” water resource systems. The steps involved in so doing are:

1. Re-scale and downscale seasonal to interannual forecasts of precipitation and surface meteorology (from the continental or regional scale climate prediction models, as shown in Figure 9.1) to the time and space scales required by macroscale hydrologic forecast models,
2. Assimilate observations (e.g. precipitation, surface meteorology, snow cover and water equivalent, streamflow and surface skin temperature) into the hydrologic forecast model(s) to estimate initial conditions,
3. Implement hydrologic models in an ensemble mode using forecasts and initial conditions, and
4. Operate a hydrologic uncertainty post processor to adjust the hydrologic forecasts to account for effects of hydrologic biases and to assure validity of probabilistic forecast information to be used by the water resources decision-makers.

The following GAPP activities are oriented toward developing the models, implementation tools, and practical understanding required to make end-to-end prediction a reality in the water management field.

9.3.1. Coupled Model Ensemble Products Analyses

This activity would analyze global and regional model ensembles from different perspectives. One important activity will involve evaluating their forecast skill and to develop quantitative measures of this. Another step will be to evaluate the validity of probabilities estimated from the ensembles and to develop methods for correcting for biases in the model forecasts. Because these ensemble products are for coarser space and time scales than the data input requirements of hydrologic forecast models, techniques to re-scale and down-scale the ensemble information will be developed and tested. This activity will be carried out in cooperation with the NWS Advanced Hydrologic Prediction System (AHPS), parts of which may be treated as an NWS contribution to the operational pathway.

9.3.2. Hydrologic Model Intercomparison Studies

A potential contribution of the extensive land surface model development accomplished during GCIP is to improve the models used in hydrologic forecasting. For example, existing hydrologic forecast models do not have well developed representations of vegetation; they do not explicitly account for energy flux and storage; and they were not designed to make use of satellite remote sensing data. On the other hand, they are explicitly designed to make good estimates of runoff and streamflow. An important next step is to compare the performance of current operational and alternative research models in terms of hydrologic forecasting.

One central element of this activity would be a Distributed Model Intercomparison Study (DMIP) that would consider alternative approaches to modeling the area upstream from several forecast points. This study would represent spatially distributed precipitation and basin characteristics at different levels of detail. The goal of such a study would be to evaluate alternative models relative to the existing NWS operational NWSRFS models when operated in both lumped and distributed modes. The results would help guide future distributed modeling research and would be used to improve the application of spatially distributed models used by operational forecasting offices.

Other model intercomparison studies would be conducted as part of the verification activity of the LDAS project. Currently, LDAS represents all of the land surface processes on a 1/8th degree grid covering the continental U.S. as well as part of Mexico and Canada. Runoff from the grid elements is routed to downstream gage or psuedo-gage locations. A number (between 100 and 200) of such locations are being identified having enough precipitation gages to assure high quality basin average precipitation estimates for use as streamflow validation sites. Intercomparisons of different models participating in LDAS will be made both retrospectively and in real time. The evaluation sites cover a range of basin sizes, generally 1000 to 10,000 sq. km. They will also include some composite areas such as the ARM/CART site where surface flux and soil moisture measurements are made as well as networks in Illinois (where a long record of soil moisture measurements is available) and the Oklahoma mesonet, which has a more recently installed soil moisture network.

9.3.3. Parameter Estimation Experiments

All land surface and hydrologic forecast models require estimation of coefficients and exponents for any practical implementation. Some model parameters can be assumed to be related to physical properties such as soils hydraulic properties or vegetation rooting depths. However, the scales at which the models are applied and the scales at which basin characteristics can be observed are vastly different. Moreover, many basin characteristics vary spatially and detailed local values are unknown. Therefore the relationships between model parameters and basin characteristics are not necessarily the same as those assumed by the land surface modeling community. Experience has shown that substantial improvements in runoff simulation can be obtained by calibrating model parameters as opposed to using existing techniques for "a priori" estimation. The objective of this activity is to improve our understanding of the relationships between model parameters and basin characteristics and to improve our understanding of what can be known through calibration about model parameters. Results of the activity will guide future research and will be used in operational meteorological and hydrological prediction systems.

9.3.4. Hydrologic Model Data Assimilation Experiments

One opportunity to improve hydrologic prediction skill is to develop better initial values of soil moisture, temperature and snow cover state variables. Although some work has been done in this area over the last two decades, the results are not widely used in operational hydrologic forecast systems. Typically, operational hydrologic forecast models use observed precipitation (and surface temperature) forcings, together with some estimate of potential evaporation to predict initial conditions at the time of the forecast. Effects of errors in the forcing values on the predicted state variables (hence streamflow) are usually dealt with manually. Methods are needed to use observed river stages, soil moisture, snow water content and snow cover, and remotely sensed surface temperatures to modify the initial values of these state variables.

Such methods must account for the effects of uncertainty in the observations, model parameters and model structure. GAPP hydrologic model data assimilation experiments are intended to be collaborative studies between academic researchers and operational hydrologists and will incorporate elements of the LDAS project as well. These activities are intended to develop improved data assimilation techniques, which would be implemented in a test environment and would serve to guide future research.

9.3.5. Water Resources Applications of Hydrologic Predictions

Application of hydrologic predictions in water resources decision analysis requires evidence of forecast skill and its quantification. Because all hydrologic models have biases, adjustments must be made to model output variables to compensate for these biases and to assure that probabilistic estimates are reliable. GCIP has initiated work (in the Ohio River basin, and elsewhere) to develop methods for quantifying and accounting for bias in climate forecasts and for describing its effects on hydrologic predictions

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A cooperative effort between NWS and NCEP is also addressing this issue, but much more needs to be done. GAPP activities in this area will evaluate the accuracy of probabilistic hydrologic predictions made using ensemble (climate and hydrologic) forecasts, with particular focus on selected water resource systems within the GAPP area. Through a parallel evaluation pathway in cooperation with selected water management agencies, these projects will evaluate uncertainties in hydrologic forecasts generated using long-lead climate forecasts and their implications for water resources decisions. Initially the primary strategy will involve retrospective analyses and evaluations of how past decisions might have been influenced by long-lead forecast information. Subsequently, long-lead and advanced hydrologic prediction capabilities will be implemented within a parallel real-time evaluation framework.

9.4. Linkages with Other Programs

The GAPP hydrology and water resources activities will be coordinated and leverage from national and international programs, as well as programs within other U.S. agencies, and elsewhere within NOAA/OGP. The most important of these linkages are outlined briefly below.

9.4.1. GEWEX and other International Programs

Within the World Climate Research Programme, GEWEX is the “parent” of GCIP and GAPP. GCIP was initially formulated as the sole Continental Scale Experiment, and has been, in some respects, the model for the other CSEs. GEWEX has always had the goal of transferring improved process understanding, as embodied in models, data products, and predictive tools, to the water resources community. At the Honolulu SSG meeting (February, 2000) GEWEX renewed its commitment to activities in the water resources area, especially evaluation and implementation of long-lead climate forecasts. As the “flagship” CSE, GEWEX looks to GCIP/GAPP for leadership in this area. The GAPP hydrology and water resources activities are designed in part to fill this need.

9.4.2. Other NOAA Programs

OGP Regional Integrated Assessment Program

The NOAA Regional Assessments Program (RAP) was formed to facilitate better interactions between three elements of OGP research: 1) climate and environmental monitoring; 2) economic and human dimensions, especially trends and factors influencing climate-sensitive human activities, and 3) applications, specifically the transformation and communication of relevant research results to meet specific needs. RAP is based on the premise that “Regions” (typically defined as subcontinental areas of which there might be about 10 within the continental U.S.A.) exist at the nexus of the local to global continuum. It is argued that the regional scale is an appropriate organizational unit at which to coordinate climate research and to provide socially relevant information that reflects geographical (e.g., river basin) and jurisdictional boundaries. RAP is made up of a set of Regional Integrated Assessments (RIAs). These RIAs are intended to characterize the current state of knowledge of climate variability, and its social and environmental impacts within a region; to assess vulnerability to climate on the seasonal and decadal to centennial time scales; to improve decision support dialogues, and to develop awareness of climate impacts on regional socioeconomic systems. RAP relies on the results and data from ongoing NOAA disciplinary process research in the physical sciences and economic and human dimensions research, and performs primarily an integrative function in this respect. This task is accomplished by means of RIAs, five of which are currently active (in the Pacific Northwest, the Southwest, Interior Mountain West, California, and the Southeast). Consistent with the theme of integration, all case studies include activities in multiple sectors (e.g., water resources, agriculture, fisheries, forestry, and others depending on the specific region). The Pacific Northwest (PNW) study is the most mature of the RIAs, and has a strong focus on hydrology and water resources. Through informal collaborations, the PNW activities have made extensive use of macroscale hydrology modeling research supported by GCIP. Water resources are likely to be an important aspect of the evolving Southwest, Interior Mountain West, and California RIAs as well.

GAPP will need to develop a protocol for interacting with RAP via the RIAs. There are important synergies between hydrologic research in GAPP and in the RIAs. For instance, at the longer time end of the prediction time scale, where RAP is concerned, with decadal to century climate variability and change, long-term climate change issues are not within GAPP's charge. On the other hand, seasonal to interannual forecasts, which have been a strong focus of the PNW RIA, are common to the two projects. One possible protocol for GAPP-RAP interaction is for GAPP to take the lead on development and testing of forecast products and RAP to lead in assessment of management and policy implications. Informally, this process has been the mechanism for interaction between GCIP and RAP in the PNW. RAP/RIA, on the other hand, could play a key role in facilitating the parallel "applications pathway" outlined in Section 9.3.

NWS Advanced Hydrologic Prediction System (AHPS)

The Advanced Hydrologic Prediction System (AHPS) is a National Weather Service Hydrology Laboratory activity that is designed to provide its users with improved hydrologic forecast information. A particular emphasis is on extending forecast lead times, producing long range forecasts and devising forecast products with formats that assist decision makers with the assessment of risk implementation and operations. In part, the motivation for AHPS comes from the increase in flood losses (which exceed $4 billion annually within the U.S. and approached $10 billion in 1997). Under a pre-AHPS pilot project, NWS has begun to implement advanced hydrologic and hydraulic models, new forecast procedures and displays, and to develop inter-agency commitments for broader implementation in its River Forecast Centers. A pilot project has been conducted on the Des Moines River, where the cooperator is the Rock Island District of the U. S. Army Corps of Engineers. AHPS first received formal funding in FY 2000, and the project team is now actively evaluating the potential for such advanced forecast methods as ensemble weather and climate forecasts. Although the focus of AHPS is primarily on flood forecasting, there is a potential convergence of interests with GAPP in the intermediate (roughly 2-week) forecast range, where some of the problems and issues surrounding use of advanced hydrologic forecast tools are common. NWS has expressed an interest in possible collaboration with GAPP, which could involve using an appropriate part of the AHPS activities as a parallel implementation and testing pathway, as outlined in Section 9.3.

9.4.3. Other U.S. Agency Programs

NASA Seasonal-to-Interannual Prediction Project (NSIPP)

NSIPP is NASA's Goddard Space Flight Center (GSFC) project that has the goal of developing an experimental short-term climate prediction capability. It is particularly focused on demonstration of the utility of satellite data, especially altimeter, air-sea flux and soil moisture observations, in a coupled land-atmosphere-ocean modeling framework. A major thrust of NSIPP is the assimilation of satellite data into the GSFC coupled atmosphere-ocean-land-ice modeling system, for the purpose of predicting not only the short term climate variations associated with SST variations in the tropical Pacific, but also those processes and teleconnections that have socio-economic impacts on the United States. There are significant opportunities for GAPP interactions with NSIPP, particularly through exploitation of opportunities for climate forecast improvements using satellite data. Furthermore, NASA has, through its Land Surface Hydrology Program, been a major source of funding for GCIP in recent years, and through that avenue, is expected to coordinate relevant GAPPP activities with NSIPP. However, in terms of the strategy shown in Figure 9.2, the NSIPP interest is in global and regional climate prediction; consequently it does not have a significant activity in the macroscale hydrologic modeling or water resources elements. In that sense, GAPP activities provide an important collaborative opportunity for NSIPP.

10. REMOTE SENSING RESEARCH AND APPLICATIONS

10.1. Introduction

Satellite data sets provide a valuable extension to conventional in-situ ground-based observations. Traditional in-situ ground observations have limitations for input, validation and assimilation in models. Point data is difficult to interpret over spatial domain of models which range from $1/8^{o}$ X $1/8^{o}$ for the high resolution Land Surface Data Assimilation Schemes (LDAS) to 2^{o} X 2.5^{o} in the case of Global Climate Models. Satellite data provides continuous spatial coverage and repeat temporal coverage. This coverage is dependent on the orbit and swath of the satellite and resolution of the sensor. EOS satellites that provide data sets on a wide number of atmospheric and land surface variables could be especially valuable for GAPP land-atmsophere modeling activities. These new data sources are the EOS Terra satellite launched in December 1999 and the EOS Aqua satellite that will be launched in December 2000. Furthermore, there are a variety of satellites launched by Japan (ADEOS II), Europe (ENVISAT), India (INSAT) that will also provide global coverage using different sensors but measure similar/same variables at different overpass times. These satellites carry new and enhanced sensors that will provide high resolution data sets and will be made available to the scientific community through the Goddard Data Active Archival Center (DAAC).

10.2. Objectives.

Within GAPP, remotely sensed satellite data will be used to:

(1) Provide input variables to offline land surface hydrological models. These input variables include, vegetation content, air temperature, precipitation, total atmospheric precipitable water content, atmospheric temperature and water vapor profile, cloud fraction and height to cloud base.

(2) Validate model outputs such as surface temperature and soil moisture content.

(3) Assimilate satellite derived products in land surface models. Products that could be assimilated include surface temperature and soil moisture.

(4) Compare satellite derived land surface products with the observations during field experiments and other data sets collected as a part of the CEOP.

10.3. Remote Sensed Data Sets

This section outlines the various variables that can be retrieved from satellite data. It is proposed that GAPP utilize single variables that may be derived from sensors with different spatial and temporal resolution and coverage and times of overpass. It should be noted that although the same data sets have been mentioned in the validation and the assimilation modes, these are designed to be complementary. The data used in the assimilation will not be used in validation and vice-versa.

10.3.1 Variables and Parameters in Land Surface Models

Land surface models require various input data sets in order to characterize the properties of the land surface as well as to provide meteorological forcings. The input data sets include:

1) Leaf area index (LAI) derived from the Normalized Difference Vegetation Index (NDVI) from the AVHRR and/or MODIS
2) Surface roughness parameters – roughness length and zero plane displacement from the Vegetation Canopy Lidar (VCL)
3) Precipitation from SSM/I and TRMM
4) Surface air temperature using TVX method from AVHRR or from the AIRS/AMSU and TOVS
5) Surface specific humidity from AIRS/AMSU and TOVS
6) Cloud cover fraction and height to cloud base derived from AIRS/AMSU, TOVS and CERES
7) Atmospheric temperature and moisture profile from AIRS/AMSU and TOVS

10.3.2 Validation Data Sets

Validation will be carried out using the following data sets:

1) Soil moisture derived using AMSR

2) Surface temperature using AVHRR, ASTER, AIRS/AMSU, MODIS, TOVS and GOES

10.3.3 Assimilation

The following data sets will be used in GAPP data assimilation activities:

1) Soil moisture derived using AMSR
2) Surface temperature using AVHRR, ASTER, AIRS/AMSU, MODIS, TOVS and GOES
3) Air temperature and specific humidity profile of the atmosphere using AIRS/AMSU

10.4. Prediction

GAPP will deal with numerous prediction issues on seasonal, annual and inter-annual time scales. The use of satellite data in prediction models will have a major impact on the accuracy of predictions. Assimilation of satellite data in real-time for soil moisture, surface temperature and precipitation will help in reducing forecast errors. These predictions and assimilation can be carried out on regional and meso scales as dictated by the particular application. In the case of detailed mesoscale applications, GOES-derived surface temperatures that have a high spatial (1km) and temporal (15 minutes) resolution will be utilized for validation and assimilation purposes. In the case of seasonal predictions, coarser data sets can be used.

The key objectives of an integrated seasonal prediction system can be realized by a better representation of the land surface system. This land surface system model will require inputs that have to be specified using satellite data. Data assimilation for the land surface will be carried out using remotely sensed data. In addition, prediction of land surface variables such as soil moisture and surface temperature can be validated using the satellite data over continental regions and extended time periods. Land surface states need to be initialized properly for accurate predictability. The initialization of land surface soil moisture and temperature can be carried out by the use of satellite data.

Multi-scale downscaling of prediction components can be carried out using satellite data at appropriate resolution. For example, a large 1o X 1o forecast of land surface evapotranspiration can be disaggregated using the 1km GOES surface temperatures and 250m MODIS vegetation indices. The potential for use of satellite data to disaggregate the model forecasts onto finer spatial resolutions will be of prime importance in the future when satellite sensor resolutions improve.

10.5. Scaling and Process Inter-Relationships

The reliance on different sensors with different spatial resolution and temporal overpass times for specific varaibles leads to a challenge in merging these data sets when they are derived from different satellites. For example, surface temperature can be derived from GOES, AVHRR, MODIS, TOVS and AIRS/AMSU and ASTER. Each of these sensors has a different spatial resolution. The spatial resolution for GOES is 1km, AVHRR is either 1km (raw data) or 4km; MODIS has the thermal bands around 1km, TOVS resolution is 60km, AIRS/AMSU is at 12.5km and ASTER is around 90m. In addition, the overpass times are different for each satellite. As a result, it will be possible to piece together the data from various satellite sensors to obtain a diurnal cycle. Therefore, it is important to merge data sets for the same variable from different satellites in time and space to create a consistent and comprehensive data set. Such a merged data set will have to ensure spatial continuity between data from different sensors and temporal continuity between data from different platforms.

Process inter-relationships can be studied using data for different variables that are related to each other. For example the relationships between precipitation, soil moisture, surface temperature and vegetation could be studied. Changes in precipitation patterns in time and space will affect vegetation, soil moisture and surface temperature. However, land-atmosphere feedback effects could result in these affected variables (vegetation, soil moisture and surface temperature) changing the precipitation patterns. Such feedbacks could be positive, i.e. changes in precipitation results in changes in the land surface variables that, in turn, could further change the precipitation. A negative feedback would result in a damping effect rather than amplification as described above. All of these variables can be derived using satellite data. Precipitation can be derived from TRMM, SSM/I, TOVS and AIRS/AMSU; soil moisture from AMSR; surface temperature sources are mentioned above and vegetation can be ascertained using AVHRR and MODIS. Regional scale process studies would focus on understanding the spatial distribution of these variables and the diurnal, seasonal and inter-annual variations of these variables. These studies will provide useful comparisons with models for process inter-relationships and will lead to better model parameterizations at a variety of space and time scales.

10.6. Support to the Coordinated Enhanced Observing Period (CEOP)

As noted earlier, GAPP along with the other GEWEX CSEs will carry out enhanced measurement programs using in-situ systems as part of CEOP. Remote sensing will be used to validate of the satellite algorithms used for retrieval of land surface variables. The validation will be carried out using these in-situ measurements. In addition, the availability of spatially distributed satellite data will help in interpolation of these point-based measurements. The satellite data are available at specific times of the data but spatially continuous. The field measurements are at a point in space but temporally continuous. Therefore, schemes that use the spatial continuity of satellite data and the temporal continuity of the field measurements will help to create data sets that can be used for various process studies. The variables that will be the focal points of such a study include (but should not be limited to) – soil moisture, surface temperature, precipitation, air temperature and specific humidity near the surface. These variables will come from a variety of satellite sensors – AMSR, AIRS/AMSU, MODIS, GOES, TOVS, AVHRR, SSM/I, TMI, ASTER etc.

11. DATA MANAGEMENT

(Chapter being written by Steve Williams)

12. LINKS with INTERNATIONAL and NATIONAL PROGRAMS:

12.1. International Linakges

12.1.1. WCRP

The World Climate Research Program (WCRP) fosters better understanding of global climate variability and change by pursuing its objective “to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of man's influence on climate.” It sponsors three “major projects” that are imprtant for GAPP including GEWEX (the Global Energy and Water Cycle Experiment), ACSYS, the Arctic Climate System Study, and CLIVAR (Climate Variability and Predictability).

12.1.1.1 GEWEX

GEWEX studies "atmospheric and thermodynamic processes that determine the Global hydrological cycle and water budget and their adjustment to global changes such as the increase in greenhouse gases”. GEWEX coordinates research designed to understand, model and predict radiative processes involving cloud, aerosol, water vapor and their impact on radiation transfer and radiation flux divergence in the atmospheric column. GEWEX also has a major focus on hydrometeorological processes, involving the transport and release heat in the atmosphere, precipitation, evapotranspiration and land surface exchanges, including water storage on and near the surface, and run-off. Within WCRP, GEWEX is the sole program with a major focus on land surface processes, and for this reason a major focus of GEWEX activities involves understanding and modeling land surface hydrology at continental and regional scales.

GEWEX is not an *experiment* in the traditional sense; rather it is an integrated *program* of research, observations, and science activities ultimately leading to prediction of variations in the global and regional hydrological regimes. GEWEX initially encouraged a suite of exploratory studies over relatively small experimental sites, involving intensive field observations and theoretical process modeling, like FIFE (First ISLSCP

Field Experiment, conducted at a Kansas grassland site in the mid 1980s), a study organized by the GEWEX International Satellite Land Surface Climatology Project (ISLSCP). Small-scale field projects like FIFE were originally expected to continue until about 2000 and then merge into a new phase of global atmospheric/hydrologic studies, relying on expected new global satellite data sets.

Just as GCIP was a central program in GEWEX, GAPP will continue strong ties to GEWEX, particularly through the GEWEX Hydrometeorology Panel. GAPP will provide leadership for CEOP and for GHP predictability studies. It will address many of the issues of concern to GEWEX and will become the GEWEX flagship activity for linking its global products and understanding to regional users and applications. GAPP will take a leadership role in meeting the objectives of the GHP Global Applications and Transferability Strategy, using its links with US Agencies to the mutual benefit of WCRP/ GEWEX and those agencies. Within GHP, GAPP will also develop strong ties with LBA for predictability and model transferability studies, MAGS and BALTEX for model transferability studies, and GAME for remote sensing and model transferability initiatives. Scientific initiatives under discussion include a transferability study in the SAGE area and the Lake Winnipeg drainage basin (including the Red River of the North) and the Rio de la Plata Basin (see Figure XX). GAPP will also contribute to the GHP through contirbutions to the Water Resources Applications Project and through individual projects such as MOPEX and data set development.

GAPP will also maintain strong ties to the CLIVAR program through VAMOS. CLIVAR is looking to GEWEX (WCRP, 1998) to provide the land components for monsoonal studies. GAPP will be an important component of VAMOS in the same way that GCIP has been. In addition, a joint CLIVAR/PACS/GAPP modeling panel will be established in order to develop a joint modeling strategy that includes both land and ocean-atmosphere feedbacks. GAPP will also assist in assessing and interpreting CLIVAR and GEWEX prediction products for water resource management applications.

12.1.1.2. CLIVAR

The overall scientific objectives of CLIVAR are to describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal and centennial time scales, through the collection and analysis of observations and the development and application of models of the coupled climate system, in co-operation with other relevant climate research and observing programs; extend the record of climate variability over the time scales of interest through the assembly of quality-controlled paleoclimatic and instrumental data sets; extend the range and accuracy of seasonal-to-interannual climate prediction through the development of global coupled predictive models; understand and predict the response of the climate system to increases of radiatively active gases and aerosols, and to compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal.

In the Pacific Sector, the Pan American Climate Study (PACS) and the Variability of the American Monsoon System (VAMOS) programs are under active development, and will be included within U.S. CLIVAR. The overall goal of PACS is to advance the understanding of seasonal and longer time scale phenomena needed to extend the scope and skill of climate prediction over the Americas, with emphasis on warm season precipitation. PACS is concentrating on the North American monsoon, including the structure and variability of the continental scale mode and the mechanisms that generate warm season precipitation anomalies. PACS is specifically concerned with explaining climatological characteristics of the atmospheric hydrologic cycle, including the relationship of the eastern Pacific coastal stratus and the continental precipitation as well as the influence of the land and ocean surface on seasonal predictability.

12.1.1.3. ACSYS/ CLIC

ACSYS is presently transitioning from a regional (Arctic drainage basin) activity to a global focus. The new WCRP programme that will eventually replace ACSYS, is termed Climate and Cryosphere (CLIC). CLIC will incorporate ACSYS sea ice and oceanographic activities in the Arctic, that will be expanded to include Antarctic research in these areas, as well as glaciers and ice sheets. Beyond shifting from a Boreal to a bipolar focus, CLIC will also include relevant cold season and regions processes elsewhere, such as glaciers in temperate regions, permafrost, and ephemeral snow cover. At its annual meeting in March, 2000, the WCRP Joint Scientific Committee approved CLIC draft Science and Coordination Plan. Version 1 of the Plan is currently available from the WCRP web site.

12.1.2. IGBP

The objective of the International Geosphere Biosphere Programme (IGBP) is "… to describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities." GAPP linkages wth IGBP are primarily through Biological Aspects of the Hydrological Cycle (BAHC).

12.1.2.1. BAHC

The BAHC core project addresses the nature of the interaction between vegetation and the hydrologic cycle. BAHC is an interdisciplinary project combining and integrating expertise from many disciplines, in particular ecophysiology, pedology, hydrology, and meteorology. In this respect BAHC cuts across disciplines as well as across spatial scales. At smaller scales, BAHC is involved in developing techniques and algorithms to provide climatic data needed at the scales of hydroecological research used to study changes of land surface conditions. At larger scales, BAHC provides soil-vegetation-atmosphere transfer models, in particular, the areal pattern of heat and moisture fluxes according to land-surface heterogeneity. BAHC is involved in these activities in a number of selected areas in the world, representing major ecosystems.

12.1.3. UNESCO

GAPP will also contribute to the UNESCO/WMO Hydrology for Environment Life and Policy (HELP) initiative by contributing to a modeling framework for HELP, using their data sets in model development and providing a link between the international water research community and climate modelers. HELP is a joint project developed under the guidance of UNESCO and endorsed by a number of agencies including WMO and the IGBP. HELP has been established to deliver social, economic and environmental benefits to stakeholders through sustainable and appropriate use of water by directing hydrological science towards improved integrated catchement management. HELP is a proactive program aimed at preparing appropriate strategies to capture climate variability and thereby provide better advice for the development of water policy. It will also address issues related to global change at the watershed scale. The agenda for research under this program will be developed through a working partnership between water policy and management and the research community. HELP will begin in 2000 and specific initiatives will be undertaken in individual basins over the next 5 years. It is anticipated that some of the Basins used for GAPP research will also contribute to the HELP objectives, and in turn that the dialogue established under HELP will advance the goals of GAPP in the area of water resource applications.

HELP catchments must provide an opportunity to study a water policy or water management issue for which hydrological process studies are needed; relevant national and local agencies must agree to cooperate in the execution of HELP; there must be adequate local capacity to participate in the program as a full partner; a minimum range of key variables and parameters must be monitored; data, information and technological expertise must be shared openly; and HELP data standards, quality assurance and quality control must be adhered to.

12.2National Programs:

12.2.1. USWRP

The U.S. Weather Research program (USWRP) provides a research focus for the ongoing modernization of the National Weather Service. USWRP is attempting to improve the specificity, accuracy, and reliability of weather forecasts using the best possible mix of modern observations, data assimilation, and forecast models. In particular, USWRP's goal is to improve forecasts of high impact weather for agriculture, construction, defense energy, transportation, public safety (emergency management), and water resource management, including floods. USWRP is especially concerned with studies related to quantitative precipitation forecasting. These studies include the measurement, estimation, and depiction of water vapor, representation of convection in forecast models and estimation of precipitation amount and type by radar and satellite. USWRP has also begun to consider the control on extreme events by surface effects, including soil/vegetation and canopy. These weather prediction research efforts complement GCIP's regional climate activities. In addition, USWRP's studies related to quantitative precipitation forecasting will help GCIP understand how to make better use of NEXRAD products. The USWRP is also beginning to coordinate its activities with the World Weather Research Programme, which is currently exploring a formal linkage with GEWEX through WMO/WCRP.

12.2.2. EOS

The Earth Observing System (EOS), in planning since the 1980s, is a NASA program (with national and international collaborators) that has entered a new stage with the launch of Terra (formerly known as EOS-AM) in December, 1999. A significant part of the EOS program is focused on observation of atmospheric and land surface phenomena, with the goal of better understanding the dynamics of the Earth’s physical climate. NASA has been a major supporter of field projects, modeling, and data assimilation activities aimed at better representing the coupled land-ocean-atmosphere system These studies have included, for instance, intensive field campaigns like FIFE, the BOReal Ecoysystem-Atmosphere Study, and LBA, which integrated in situ observations with aircraft and satellite remote sensing. The International Satellite Land Surface Climatology Project (ISLSCP) has had major support from NASA. NASA also provides data products and analyzed fields essential to the success of GCIP, notably diagnostics of cloud amount and properties through the International Satellite Cloud Climatology Project (ISCCP), surface radiation flux estimates (Langley Research Center) and soil/hydrology/vegetation data (Huntsville Global Hydrology and Climate Center). Conversely, it is expected that GCIP multi-disciplinary studies and data products will provide a high quality benchmark for the validation of EOS observations for Terra, EOS-PM, and other missions like the Tropical Rainfall Monitoring Mission (TRMM).

12.2.3. Integrated Reginal Assessemnts:

NOAA, through its Office of Global Programs, supports integrated scientific assessments of the effects of climate variability and change on the natural and managed environment. These continuing projects are designed to characterize the state of knowledge of climate variations and changes at regional scales, to identify knowledge gaps and linkages in selected climate-environment-society interactions, and to provide an informed basis corresponding to climate-related risks. At present, there are five regional integrated science and assessments activities funded by NOAA-OGP. These assessments are focused on the Pacific Northwest, the Southwest, California, Inter-Mountain West, and the Southeast regions of the United States.

12.2.4. Advanced Hydrologic Prediction Systems

Within the National Weather Service Office of Hydrology (NWS/OH), the Advanced Hydrological Prediction System (AHPS) is seeking to improve the state of the art of hydrologic prediction as applied primarily to flood forecasting. Although NWS/OH does not formally suppport extramural research, it is cooperating with the academic community in the development of AHPS, in particular through an evolving partnership with GCIP/GAPP.

12.2.5. Atmospheric Radiation Program (ARM):

The Department of Energy funds the Atmospheric Radiation Measurement (ARM) program which is intended to improve understanding of the transfer of radiation through the atmosphere. A central ARM component is the Cloud and Radiation Testbed (CART) concept, which is currently underway at sites in the Southern Great Plains (SGP) of south central Kansas and central Oklahoma, the North Slope of Alaska, and a Tropical Western Pacific site. The CART sites provides surface radiation flux data, as well as boundary layer soundings, at multiple observing locations. Enhanced observations are collected during Intensive Observation Periods (IOP) of a few weeks at several times during each year. At the SGP CART site, observations are coordinated with GCIP studies of summer rainfall and re-evaporation.

13. PROGRAM IMPLEMENTATION:

GAPP will be phased in during 2001 as GCIP begins to be phased out. This transition must be smooth to ensure that the GCIP community and the principal funding agencies, NOAA and NASA, derive the full benefits of the investment they have been made in GCIP. The management of GAPP will be built on the successful aspects of the GCIP management structure. In particular GAPP will have:

- Scientific Steering Committee (SSC) (whose members will be chosen from the scientists currently working with GCIP and other scientists specializing in related subject areas such as predictability) and several working groups (principal research areas) including one that would report to both the GAPP SSC and the PACS SSC.
- A link with the US Water Cycle Initiative and the Infrastructure developed to support that program (e.g. project office, interagency committee)
- A program office that will link GAPP to other US and international initiatives, and provide liaison with funding agencies and, where appropriate, international bodies, has been recommended (but is not approved by agencies). This office would also organize planning and science meetings, coordinate the preparation of program plans, develop syntheses of the scientific results, provide information to PIs through newsletters, information bulletins and a home page, coordinate evaluations and provide scientific and programmatic advice to federal funding agencies.

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APPENDIX A

GAPP DELIVERABLES

2002: Products from a land data assimilation system for climate research.

2003: An assessment of the best approach for working with water resource agencies and organizations based on demonstration projects linking climate predictions and water resource management in the Mississippi River Basin

2004: Modified land surface and hydrologic models based on data and process studies in arid regions.

2004: Initial results from model transferability studies based on data from the WCRP/ GEWEX Coordinated Enhanced Observing Program.

2004: An understanding of the role of land processes in the North American Monsoon.

2005: Modified land surface and hydrologic models based on data and process studies in the Pacific coastal areas.

2006: Development of an integrated land surface model that accounts for the different processes found in the GEWEX Continental-scale Experiments and the utilization of these models together with global models in a nested mode.

2006: An integrated approach for modeling surface and subsurface hydrology in climate models.

2006: An understanding of the role of land in the dynamics and thermodynamics of the Low Level Jet in the central USA and its contribution to the climate of the USA on time scales up to annual.

2007: Assessment of the integrated effects of land-atmosphere processes for North America and the world.

2007: Through collaboration with CLIVAR, successful testing of a global climate prediction system which properly accounts for land-atmosphere coupling.

2007: Delivery of meaningful hydrologic prediction products through participation in the WMO/ UNESCO Hydrology for Environment, Life and Policy (HELP).

APPENDIX B

ACRONYMS

ADEOS	Advanced Earth Observing Satellite II
AIRS	
AMERIFLUX	American Flux (Network)
AMSU	
ARM	Atmospheric Radiation Measurement
ASCOT	
ASTER	
AVHRR	Advanced High Resolution Radiometer
AZNM	
BALTEX	Baltic Sea Experiment
BoR	Bureau of Reclamation
CART	Clouds and Radiation Testbed
CASES	Cooperative Atmosphere-Surface Exchange Study
CATCH	
CEOP	Coordinated Enhanced Observing Period
CERES	
CLIVAR	Climate Variations
CLM	Common Land Model
COHS	
COLA	Center for Ocean, Land Atmosphere
CPC	Climate Prediction Center
CSE	Continental Scale Experiment
DAAC	
DAO	Data Assimilation Office
DMIP	

DOE	Department of Energy
ECMWF	European Center for Medium Range Weather Forecasts
ENSO	El Niño Southern Oscillation
ENVISAT	
EOS	Earth Observing System
FSL	Forecast Systems Laboratory
GAME	GEWEX American Monsoon Experiment
GAPP	GEWEX America Prediction Project
GCIP	GEWEX Continental-scale International Project
GCLLJ	Gulf of California Low Level Jet
GCM	General Circulation Model
GDAS	Global Data Assimilation System
GEM	Global Environmental Multi-scale Model
GEWEX	Global Energy and Water Cycle Experiment
GHP	GEWEX Hydrometeorology Panel
GOES	
GPLLJ	Great Plains Low Level Jet
GSFC	Goddard Space Flight Center
GSWP	GEWEX Soil Wetness Project
HELP	Hydrology for Environment, Life and Policy
IGPO	International GEWEX Project Office
INSAT	
IPCC	Intergovernmental Panel on Climate Change
IPEX	
IRI	International Research Institute
ISA	
ITCZ	Intertropoical Convergence Zone
IV-SVATS	
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LBC	
LDAS	Land Data Assimilation System
LLJ	Low-Level Jet

LLNL	
LSA	Large Scale Area
LSM	Land Surface Model
JMC	Japanese Meteorological Center
MAGS	Mackenzie GEWEX Study
MAPS	Meterological …. Prediction System
MSC	Meteorological Services of Canada
MHM	
MJO	Madden Jullien Oscillation
MODIS	
NAME	North American Monsoon Experiment
NAMS	North American Monsoon System
NAS	
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDVI	
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWSRFS	
ODAE	
OGP	Office of Global Programs
OH	Office of Hydrology
PACS	Pan American Climate Studies
PDO	Pacific Decadal Oscillation
PI	Principal Investigator
PILPS	Project for the Intercomparison of Land Surface Parameterization Schemes
PNA	Pacific North American (Teleconnection)

PNW	Pacific Northwest
QPF	Quantitative Precipitation Forecasts
RAMS	Regional Atmospheric Modeling System
RAP	
RIA	
RMM	Regional Mesoscale Model
SALSA	Semi-Arid Land Surface Atmosphere Program
SSC	Scientific Steering Committee
SST	Sea Surface Temperature
SSTA	
SVATS	
TEW	Tropospheric Easterly Wave
TOGA	Tropical Ocean Global Atmosphere
TOVS	
TVX	
UCL	
UNESCO	United Nations Education Science and Culture Organization
USA	United State of America
USACE	US Army Corps of Engineers
USDA	United States Department of Agriculture
USGCRP	United State Global Change Research Program
USGS	United States Geological Survey
VAMOS	Variability of the American Monsoon System
VTMX	
WCRP	World Climate Research Programme
WMO	World Meteorological Association

Appendix C: The North American Monsoon System

C.1 Life Cycle

The life-cycle and large-scale features of the NAMS can be described using terms typically reserved for the much larger Asian Monsoon system; that is, we can characterize the life-cycle in terms of development, mature and decay phases. The development (May-June phase) is characterized by a period of transition from the cold season circulation regime to the warm season regime. This transition is accompanied by a decrease in mid-latitude synoptic-scale transient activity over the conterminous United States and northern Mexico as the extratropical storm track weakens and migrates poleward to a position near the Canadian border by late June (e.g. Whittaker and Horn 1981; Parker et al. 1989). During this time there are increases in the amplitude of the diurnal cycle of precipitation (e.g. Wallace 1975; Higgins et al. 1996) and in the frequency of occurrence of the Great Plains low-level jet (e.g. Bonner 1968; Bonner and Paegle 1970; Augustine and Caracena 1994; Mitchell et al. 1995; Helfand and Schubert 1995; Higgins et al. 1997a). The onset of the Mexican Monsoon (Douglas et al. 1993; Stensrud et al. 1995) is characterized by heavy rainfall over southern Mexico, which quickly spreads northward along the western slopes of the Sierra Madre Occidental into Arizona and New Mexico by early July (Fig. 1). Precipitation increases over northwestern Mexico coincide with increased vertical transport of moisture by convection (Douglas et al. 1993) and southerly winds flowing up the Gulf of California (Badan-Dagan et al. 1991). Increases in precipitation over the southwestern United States coincide with the development of a pronounced anticyclone at the jet stream level (e.g. Okabe 1995), the development of thermally induced trough in the desert Southwest (Tang and Reiter 1984; Rowson and Colucci 1992), northward displacements of the Pacific and Bermuda Highs (Carleton 1986; 1987), the formation of southerly low-level jets over the Gulf of California (Carleton 1986; Douglas 1995), the formation of the Arizona monsoon boundary, and increases in eastern Pacific sea surface temperature gradients (Carleton et al. 1990). From June to July there is also an increase in sea-level pressure over the southwestern United States (Okabe 1995) and a general height increase in mid-latitudes associated with the seasonal heating of the troposphere. The largest increases in height occur over the western and southern United States and are likely related to enhanced atmospheric heating over the elevated terrain of the western United States and Mexico, and increased latent heating associated with the development of the Mexican Monsoon. The resulting middle and upper tropospheric “monsoon high” is analogous to the Tibetan High over Asia (e.g. Tang and Reiter 1984) and the warm season Bolivian High over South America (e.g. Johnson 1976).

During the mature (July-August) phase the NAMS is fully developed and can be related to the seasonal evolution of the continental precipitation regime. The monsoon high is associated with enhanced upper tropospheric divergence in its vicinity and to the south, and with enhanced easterlies (or weaker westerlies) and enhanced Mexican Monsoon rainfall (Douglas et al. 1993). To the north and east of the monsoon high, the atmospheric flow is more convergent at upper levels and rainfall diminishes from June to July in the increasingly anticyclonic westerly flow (e.g. Harman 1991). Surges of maritime tropical air northward over the Gulf of California are linked to active and break periods of the monsoon rains over the deserts of Arizona and California (Hales 1972). The mature phase has also been linked with increased upper-level tropospheric divergence and precipitation in the vicinity of an “induced” trough over the eastern United States.

The decay (September-October) phase of the NAMS can be characterized as the reverse of the onset phase, although the changes tend to proceed at a slower rate. During this phase the ridge over the western United States weakens as the monsoon high retreats southward and Mexican Monsoon precipitation diminishes. The decay phase is also accompanied by an increase in rainfall over much of the surrounding region (Okabe 1995).

Numerous authors have attempted to identify the primary source of moisture for the summer rains over the southwestern United States. Bryson and Lowery (1955) suggested that horizontal advection of moist air at middle levels from the east or southeast around a westward extension of the Bermuda high might explain the onset of summer rainfall over the Southwest; this idea was later corroborated by Sellers and Hill (1974). Several authors (Hales 1972, 1974; Brenner 1974; Douglas et al. 1993) expressed skepticism for this type of explanation since moisture from the Gulf of Mexico would first have to traverse the Mexican

Plateau and Sierra Madre Occidental before contributing to Arizona rainfall. Rasmusson (1966; 1967) was among the first to show a clear separation between water vapor east of the continental divide, that clearly originates from the Gulf of Mexico / Caribbean Sea, and moisture over the Sonoran Desert that appears to originate from the Gulf of California. Schmitz and Mullen (1996) examined the relative importance of the Gulf of Mexico, the Gulf of California and the eastern tropical Pacific as moisture sources for the Sonoran Desert using ECMWF analyses. They found that most of the moisture at upper levels over the Sonoran desert arrives from over the Gulf of Mexico, while most of the moisture at lower levels comes from the northern Gulf of California.

Berbery (2000) used the Eta model Data Assimilation System (EDAS) to show that the diurnal cycle in moisture flux divergence over the core monsoon region is related to the diurnal cycle in the sea breeze / land breeze circulation. In particular, the afternoon seabreeze is associated with strong moisture flux divergence over the Gulf of California and strong moisture flux convergence over the west slopes of the Sierra Madre Occidental leading to intense afternoon and evening precipitation (Fig. 2). At night the land breeze develops leading to moisture flux convergence near the coastline and over the Gulf of California where morning precipitation often develops.

C.2 Continental-scale Precipitation Pattern

The onset of the summer monsoon rains over southwestern North America has been linked to a decrease of rainfall over the Great Plains of the U.S. (e.g., Tang and Reiter 1984; Douglas et al. 1993; Mock 1996; Higgins et al. 1997b) and to an increase of rainfall along the East Coast (e.g., Tang and Reiter 1984; Higgins et al. 1997b). Okabe (1995) has shown that phase reversals in this continental-scale precipitation pattern are related to the development and decay of the monsoon. Changes in the upper-tropospheric wind and divergence fields (mean vertical motion) are broadly consistent with the evolution of this precipitation pattern (Fig. 3) (Higgins et al. 1997b).

Recently, Higgins et al. (1998) demonstrated that interannual variability of the continental-scale precipitation pattern closely mimics the seasonal changes associated with the development of the NAMS, suggesting that summer drought (flood) episodes in the central U.S. are linked to an amplification (weakening) of the NAMS and, in particular, to the intensity of the monsoon anticyclone over the southwestern U.S. It is important to determine to what extent this pattern is captured in global and regional models.

C.3 Interannual Variability

There is a growing body of modeling and observational evidence that slowly varying oceanic boundary conditions (i.e., SST, sea ice) and land boundary conditions (e.g. snow cover, vegetation, soil moisture and ground water) influence the variability of the atmospheric circulation on time scales up to seasonal and annual (e.g. Yasunari 1990; Yasunari et al. 1991; Yasunari and Seki 1992). Within the context of the NAMS, Higgins et al. (1998) showed that wet (dry) summer monsoons in the southwestern U.S. tend to follow winters characterized by dry (wet) conditions in the southwestern U.S. and wet (dry) conditions in the northwestern U.S. (Fig. 4) This association was attributed, at least in part, to the wintertime pattern of Pacific SST anomalies (SSTA) which provide an ocean-based source of memory of antecedent climate fluctuations.

A number of studies have considered the simultaneous relationship between SST in the tropical Pacific and NAMS rainfall. Harrington et al. (1992) found significant correlations between the phase of the southern oscillation and AZNM precipitation. Hereford and Webb (1992) suggested a relationship between increased summer precipitation in the Colorado plateau region and the warm phase of ENSO. During the summer season other studies have argued that more localized SSTA are important. Carleton et al. (1990) showed that the Southwest Monsoon is negatively correlated with SSTA along the northern Baja coast, while Huang and Lai (1998) found positive correlations with SSTA over the Gulf of Mexico. Ting and Wang (1997) found that SSTA in the North Pacific may also influence precipitation over the central United States.

Another possibility is that both winter and summer precipitation regimes are influenced by coherent patterns of SSTA that persist from winter to summer. Namias et al. (1988) emphasized that persistent SSTA patterns in the North Pacific are often associated with persistent atmospheric teleconnection patterns. They identified the region in the midlatitudes of the central North Pacific (near 40o N) as being an important area where SSTA have an effect on circulation anomalies downstream over the U.S. Of particular relevance for the NAMS is the work of Carleton et al. (1990) who demonstrated that anomalously wet (dry) summers in Arizona tend to follow winters characterized by the positive (negative) phase of the Pacific-North America teleconnection pattern.

Monsoonal rains are also influenced by changes in land-based conditions that provide memory of antecedent hydrologic anomalies. Observational and modeling evidence indicates that the springtime snowpack across Eurasia modulates the amplitude of the Asian monsoon rains in the following summer, such that heavy snowpack leads to a weak monsoon, and light snowpack leads to a strong monsoon (e.g., Barnett et al. 1989; Vernekar et al. 1995; Yang et. al 1996). Gutzler and Preston (1997) found an analogous relationship in North America such that excessive snow in the west-central U.S. leads to deficient summer rain in the Southwest and deficient snow leads to abundant summer rain.

Seasonal weather prediction has also been shown to be dependent, at least in portions of the land, on the soil moisture at the beginning of the growing season (Pielke et al. 1999) and the feedback between vegetation growth and rainfall (Eastman et al. 2000, Lu et al. 2000). This feedback may explain why correlations between ocean sea surface temperatures and rainfall over the Great Plains and southwest United States deteriorate during the warm season (Castro et al. 2000). The inclusion of models of the vegetation response to weather, and the subsequent feedback to rainfall and other weather variables, therefore, may improve seasonal weather prediction. To accomplish this goal, however, soil physics and vegetation dynamics must be included as seasonal weather variables in the same context as rainfall, temperature, and other atmospheric variables.

C.4 Decadal Variability

Latif and Barnett (1996) discussed two types of decadal variability in the North Pacific that may be relevant for the NAMS. The first is associated with the recent climate shift in the North Pacific in the mid-1970s (e.g. Trenberth and Hurrell 1994; Miller et al. 1994; Graham et al. 1994) which many authors agree is a manifestation of atmospheric forcing driving ocean variations. The second type is more oscillatory, and involves unstable ocean-atmosphere interactions over the North Pacific as originally hypothesized by Namias (1959). Namias argued that SSTA in the North Pacific influence the atmospheric transients, hence the mean westerly flow in such a way as to reinforce the original SSTA. Recent coupled GCM and observational studies (e.g. Latif and Barnett 1994; 1996) have implicated Namias's hypothesis in the decadal variability of the North Pacific-North American sector.

In a recent study Higgins and Shi (1999) argued that the summer monsoon in the southwest U.S. is modulated by longer term (decade-scale) fluctuations in the North Pacific SSTs associated with the Pacific Decadal Oscillation. They found that the mechanism relating the North Pacific wintertime SST pattern to the summer monsoon appears to be via the impact of variations in the Pacific jet on west coast precipitation regimes during the preceding winter . This mechanism affects local land-based sources of memory in the southwestern U.S., which in turn influence the subsequent timing and intensity of the summer monsoon.

Occasionally long-term (decade-scale) periods of persistent drought or rainy conditions occur in the southwestern U.S. The reasons for such climate anomalies are poorly understood, and the modulation of interannual variability by longer term climate fluctuations also needs to be examined as part of the broader effort to develop useful short-term climate prediction capabilities. At the present time it is unclear whether any of the links between the monsoon in the southwestern U.S. and antecedent conditions are robust enough to have a positive impact on the predictability of warm season precipitation. Nevertheless, these relationships need to be described and sorted out.

C.5 Intraseasonal Variability

The intensity of the seasonal mean monsoon is influenced by the nature of the variability within the monsoon season. Previous attempts to relate rainfall anomalies for the monsoon season to the date of onset of the Indian monsoon (e.g. Dhar et al. 1980) have generally shown little relationship indicating that the intraseasonal variability of monsoon rainfall is quite large. In other words, a season with deficient monsoon rainfall does not imply an absence of rainfall for the whole season, but rather prolonged periods of reduced rainfall often referred to as “break” monsoons; prolonged periods of enhanced rainfall are referred to as “active” monsoons. Douglas and Englehart (1996) demonstrated that a dominant mode of variability of summer rainfall in Southwest Mexico was a tendency for an alternating wet-dry-wet period in the July-August-September time frame. The NAMS exhibits a pronounced double peak structure in precipitation and diurnal temperature range equatorward of the Tropic of Cancer (Fig. 5) but the physical setting responsible for this intraseasonal variability remains elusive.

Stensrud et al. (1995) showed that a mesoscale model can simulate the observed features of the NAMS, including southerly low-level flow over the Gulf of California, the durnal cycle of convection, and a low-level jet that develops over the northern end of the Gulf of California. One particularly important mesoscale feature that the model reproduces is a gulf surge, a low-level, northward surge of moist tropical air that often travels the entire length of the Gulf of California. Common characteristics of these disturbances (Hales 1972 and Brenner 1974) include changes in surface weather (a rise in dewpoint temperature, a decrease in the diurnal temperature range, a windshift with an increased southerly wind component, and increased cloudiness and precipitation). Gulf surges appear to promote increased convective activity in Arizona and are related to the passage of Tropical Easterly Waves (TEWs) across western Mexico (Fig. 6; Stensrud et al. 1997; Fuller and Stensrud 2000).

One aspect of the connection between gulf surges and TEWs that has not been explored systematically is the extent to which it might influence the interannual variability in the onset and intensity of the monsoon. Since TEWs and Gulf surges are most active during the summer months, they are most likely to play a role in the onset of the monsoon in the southwestern US, which typically begins in early July. In addition, the extent to which TEWs might help explain the midsummer transitions over southern Mexico and central America also needs to be explored.

In a recent study Higgins and Shi (2000) separated the dominant modes of intraseasonal and interannual variability of the North American monsoon system (NAMS) in order to examine MJO-related and ENSO-related influences on U.S. weather during the summer months. They found a strong relationship between the leading mode of intraseasonal variability of the NAMS, the Madden-Julian Oscillation (MJO), and the points of origin of tropical cyclones in the Pacific and Atlantic basins (Fig. 7) which should be examined further.

C.6 Modeling

a. Limited-area models

In addition to the mesoscale modeling work of Stensrud et al. (1997) and Fuller and Stensrud (2000) discussed in the previous subsection, Small (2000) used the MM5 model linked to the OSU land surface scheme in season-long experiments designed to investigate the effects of soil moisture anomalies on the NAMS. Results showed that monsoon response to soil moisture anomalies depends strongly on the location of the surface forcing. Positive (negative) soil moisture anomalies within the NAMS region enhance (inhibit) summertime precipitation in that region, consistent with previous studies (e.g. Betts and Ball 1998). In contrast, positive (negative) soil moisture anomalies in the southern Rocky Mountains inhibit (enhance) monsoon precipitation, consistent with the findings of Gutzler and Preston (1997) regarding snow cover (hence soil moisture) effects on the NAMS.

b. Global models

Boyle (1998) analyzed the annual cycle of precipitation over the southwestern U.S. in output from 30 GCMs participating in the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). Results tended to improve with finer resolution, although fine resolution was neither necessary nor sufficient to produce a precipitation trend consistent with observations. Arritt et al. (2000) examined the NAMS in ten-year records for control climate and enhanced greenhouse-gas scenarios from the Hadley Centre coupled ocean-atmosphere GCM. They found that precipitation trends and dynamical response to the NAMS were reasonably well represented for current climate (Fig. 8), and that the NAMS signal was stronger in the greenhouse-gas scenario.

Yang et al. (2000) found that summertime precipitation associated with the NAMS was largely under represented in simulations using the NCAR Community Climate Model version 3 (CCM3) forced with prescribed sea surface temperatures. Diagnostic analyses suggest that excessive convection over the eastern Pacific and the Caribbean produces excess subsidence over much of northern Mexico and the southwestern United States, and prohibits the northward transport of atmospheric moisture into the NAMS region. Using an experimental semi-Lagrangian version of CCM3, Hahmann et al. (1999) carried out climate simulations at high (T63L and T127L) and ultra-high (T191L) resolutions. Over the southwestern United States, while the simulation of wintertime precipitation appears to improve with increased resolution, the southwest summer monsoon is consistently under represented.

APPENDIX D

North American Monsoon Experiment (NAME)

The North American Monsoon Experiment (NAME) is an internationally coordinated field program designed to (i) monitor, quantify and analyze low-level circulations that modulate monsoon precipitation, (ii) understand the role of the North American monsoon in the global water and energy cycles, and (iii) improve the simulation and monthly-to-seasonal prediction of the monsoon and regional water resources. At the present time a NAME Implementation Plan is under development.

By design, NAME will link CLIVAR/VAMOS, which has an emphasis on ocean-atmosphere interactions with GEWEX/GAPP, which has an emphasis on land-atmosphere interactions in order to determine the relative importance of the coupled interactions between the ocean, land and atmosphere as they relate to the monsoon. NAME will benefit from linkages to other ongoing projects within GAPP, including the LDAS and the NCEP Regional Reanalysis and from linkages to other field programs within CLIVAR/VAMOS, such as the American Low- level Jets (ALLS) and VEPIC.

Some anticipated benefits from NAME include (i) a better understanding of key components of the NAMS and their variability; (ii) a better understanding of the role of the NAMS in the global water cycle; (iii) improved observational data sets of the regional circulations and moisture cycles that will contribute to more successful weather and climate forecasts (i.e. added skill in predictions up to seasonal) and (iv) improved modeling of key monsoon features and their variability, including the diurnal cycle of convection.

Among the questions relating to warm season precipitation predictability that will be addressed by NAME:

1. How are the Gulf of California (GOC) sea breeze / land breeze circulations related to the diurnal cycle of moisture and convection?

2. What role does the GOC low-level jet play in the summer precipitation and hydrology of southwestern North America?

3. How do interactions between tropical easterly waves and GOC surge events contribute to monsoon precipitation along the GOC?

4. What are the dominant sources of precipitable moisture for monsoon precipitation?

5. To what extent are active / break cycles in the monsoon modulated by intraseasonal fluctuations in the eastern Pacific warm pool?

6. What role do regional variations in land surface parameters (e.g. soil moisture, soil temperature; vegetation biomass) play in modulating monsoon precipitation?

7. How important are relationships between intraseasonal variability of the NAMS, the MJO, and tropical cyclone activity in the Pacific and Atlantic basins?

NAME activities will include planning, preparation, data collection and principal research phases. NAME planning will include the development of a NAME Science and Implementation plan and a CLIVAR/GEWEX Planning Workshop to consider the plan. NAME preparations will include a build-up phase leading to a two-summer Enhanced Observing Period (EOP). The NAME principal research phase will continue for several years following the data collection phase, culminating in a NAME Research Conference. A timetable for NAME activities is being developed for the NAME Science and Implementation Strategy.

A multiscale approach to the analysis, diagnostic and model development activities of NAME, similar to that used by the GCIP Continental Scale Experiments (CSEs), is recommended. NAME will identify two different spatial scales. Reference sites will consist of well instrumented locations of small to intermediate scale areas (10**4 km or less) distributed around the Gulf of California, Baja and western Mexico. These sites will provide data on the mesoscale (and smaller) for research in land area and hydrology processes and model validation.

Larger Regional Scale Areas (i.e. larger fractions of the NAMS domain) will be chosen as a function of the research objective. A two-year period (possibly 2003-2004) has been identified as providing an excellent opportunity to carry out NAME data collection because (i) a new generation of remote sensing satellites will be available to provide unprecedented enhancement of observing capabilities to quantify critical atmospheric, surface, hydrologic and oceanographic parameters; (ii) several NWP centers (e.g. NCEP, ECMWF) are able to run their coupled modeling system to provide dynamically consistent datasets over the NAMS domain, and (iii) other GEWEX/GAPP and CLIVAR/VAMOS field experiments are planned during this period.

The components and scope of the observational effort will be closely linked to the magnitude of the overall effort. For NAME the observational approach will focus on short-term observations. For reference sites within the NAMS domain, well-instrumented locations in different climatic regimes can provide the data needed on the mesoscale and / or smaller scale. For regional scales ranging from a subarea of the NAMS domain to the NAMS domain, less extensive instrumentation is required; some augmentation will be required above the standard observational networks.

APPENDIX E WEB SITES

There are numerous traditional publications associated with each of the programs described throguhout this document. For more details on specific programs the reader is referred toinformation on these programs through their web sites.

INTERNATIONAL PROGRAMS
ACSYS: http://www.npolar.no/acsys/
BAHC: http://www.pik-potsdam.de/~bahc/
CLIVAR: http://www.dkrz.de/clivar/hp_nf.html
GCOS: http://www.wmo.ch/web/gcos/gcoshome.html
GEWEX: http://www.gewex.com
HWRP: http://www.wmo.ch/web/homs/hwrphome.html
HELP: http://www.unesco/science/help
IGBP: http://www.igbp.kva.se/progelem.html
IHP: http://www.nfr.se/internat/ihp_igbp/IHPindex.html
WCRP: http://www.wmo.ch/web/wcrp/wcrp-home.html
WMO: http://www.wmo.ch/

US NATIONAL PROGRAMS
ARM: http://www.arm.gov/
EOS: http://eospso.gsfc.nasa.gov/
GCIP/GAPP: http://www.gewex.com/gcip.html
U.S. CLIVAR: http://www.clivar.ucar.edu/hp.html
USDA-ARS: http://www.nps.ars.usda.gov/programs/201s2.htm
USGS-NRP: http://water.usgs.gov/nrp/
USWRP: http://box.mmm.ucar.edu/uswrp/

APPENDIX F

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